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

M. Aaboud et al.
(ATLAS Collaboration)
(Received 6 July 2017; published 1 November 2017)

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.

DOI: 10.1103/PhysRevLett.119.181804

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 $E_T^{\text{miss}}$ 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 $\mathcal{B} = 57\%$ [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 $h \rightarrow b\bar{b}$ and $h \rightarrow \gamma\gamma$ 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 $M$. 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 $E_T^{\text{miss}}$ 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, $\tan\beta = 1$, $g_{Z'} = 0.8$, $m_H = m_{H^0} = 300$ 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, \( V + \) 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 \( gg \rightarrow Vh \), and POWHEG interfaced to PYTHIA 8.186 using CT10 PDFs for \( gg \rightarrow Vh \).

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 \( h \rightarrow bb \) 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 \( h \rightarrow bb \) 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, \( p_T^{\text{miss,trk}} \) 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 \( E_T^{\text{miss}} \), 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 \( Z(\nu\nu) + \) jets, \( W + \) jets, and \( t\bar{t} \) production contribute, respectively, 30%–60%, 10%–25%, and 15%–50% of the total background, depending on \( E_T^{\text{miss}} \) 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 (1\( \mu \)-CR) is designed to constrain the \( t\bar{t} \) and \( W + \) jets backgrounds, while the two-lepton control region (2\( e\)-CR) constrains the \( Z + \) jets 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, \( \Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss,trk}}) < \pi/2 \), and \( p_T^{\text{miss,trk}} > 30 \) GeV for events with fewer than two central \( b \)-tagged small-\( R \) jets. The requirements using \( p_T^{\text{miss,trk}} \) 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 $\Delta\phi(E^{\text{miss}}_T,p_T^{\text{jet}}) < \pi/8$, 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 $h \rightarrow bb$ 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 × $H_T^{\text{alljets}}$. Finally, $\Delta R(p_T^{h_1},p_T^{h_2}) < 1.8$ 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 $\tau$-lepton candidates with $\Delta R(p_T^{h},p_T^{\tau}) > 1.0$ are vetoed; no $b$-tagged central small-$R$ jets with $\Delta R(p_T^{b-tag},p_T^{\tau}) > 1.0$ are allowed in the event; and the scalar sum of $p_T$ of the small-$R$ jets with $\Delta R(p_T^{h},p_T^{\tau}) > 1.0$ is required to be smaller than 0.57 times that sum added to $p_T^{\tau}$.

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 $Z \rightarrow \nu\bar{\nu}$ decays in the SR, the $E_T^{\text{miss}}$ is set to the $p_T$ 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 $[\Delta\phi(E^{\text{miss}}_T,p_T^{\text{jet}})]$ 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 [70,71]; 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 $E_T^{\text{miss}} > 300$ 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 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 $(m_{Z'},m_A)=(2.6,0.3 \text{ TeV})$. 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 $E_T^{\text{miss}}$.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Impact [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>$V +$ jets modeling</td>
<td>5.0</td>
</tr>
<tr>
<td>$t\bar{t}$, single-$t$ modeling</td>
<td>3.2</td>
</tr>
<tr>
<td>SM $Vh(bb)$ normalization</td>
<td>2.2</td>
</tr>
<tr>
<td>Signal modeling</td>
<td>3.9</td>
</tr>
<tr>
<td>MC statistics</td>
<td>4.9</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.2</td>
</tr>
<tr>
<td>$b$ tagging, track jets</td>
<td>1.4</td>
</tr>
<tr>
<td>$b$ tagging, calo jets</td>
<td>5.0</td>
</tr>
<tr>
<td>Jets with $R=0.4$</td>
<td>1.7</td>
</tr>
<tr>
<td>Jets with $R=1.0$</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>10</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>6</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>12</td>
</tr>
</tbody>
</table>
normalizations of $t\bar{t}$ considered in the latter process due to PDFs [80]. Only the total event yield is reduced by up to 30% at high $E_T$. The normalizations of $\tau\tau$, $W +$ jets, and $Z +$ jets 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 $\tau\tau$ is reduced by up to 30% at high $E_T^{\text{miss}}$. 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 $E_T^{\text{miss}}$ 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 $\mathcal{B}(h \to b\bar{b})$ with the CLs formalism [81] using a profile likelihood ratio [82] as test statistic. Exclusion contours in the $(m_Z, m_A)$ plane 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 $E_T^{\text{miss}}$.

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 $E_T^{\text{miss}}$ 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).

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 $m_j = 100$ 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 $\sigma_{\text{vis},k(b)b} + DM \equiv \sigma_{h + DM} \times B(h \rightarrow b\bar{b}) \times A \times \epsilon$ of $h(b\bar{b}) + DM$ events. Also shown are the acceptance $\epsilon$ to reconstruct and select an event in the same $E_T^{\text{miss}}$ bin as generated.

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV)</th>
<th>$\sigma_{\text{vis},k(b)b} + DM$</th>
<th>$\sigma_{h + DM} \times B(h \rightarrow b\bar{b}) \times A \times \epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[150, 200)</td>
<td>19.1</td>
<td>18.3$^{+7.2}_{-5.1}$</td>
</tr>
<tr>
<td>[200, 350)</td>
<td>13.1</td>
<td>10.5$^{+5.4}_{-2.9}$</td>
</tr>
<tr>
<td>[350, 500)</td>
<td>2.4</td>
<td>1.7$^{+0.7}_{-0.5}$</td>
</tr>
<tr>
<td>[$\infty$, $\infty$)</td>
<td>1.7</td>
<td>1.8$^{+0.7}_{-0.5}$</td>
</tr>
</tbody>
</table>

from DM particles. For this, limits are set on $\sigma_{\text{vis},k(b)b} + DM \equiv \sigma_{h + DM} \times B(h \rightarrow b\bar{b}) \times A \times \epsilon$ of $h(b\bar{b}) + DM$ 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 $\sigma_{\text{vis},k(b)b} + DM$ 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 $h + DM$ signal, the standard fit approach is modified to analyze one $E_T^{\text{miss}}$ range at a time in the SR. The $Z^\prime$-2DM model is used to evaluate the dependence of the $\sigma_{\text{vis},k(b)b} + DM$ 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 $10% \times \sigma_{h + DM} \times B(h \rightarrow b\bar{b})$ 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 $p_{T,h} \lesssim 1.5$ 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 $h \rightarrow b\bar{b}$ 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 $Z^\prime$-2DM 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.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; STFC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; SRNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, USA. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FPT, Horizon 2020 and Marie Sklodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleiteos, Thales and Aristoteles programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in 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 \(p_T = p \sin \theta\).


[34] CMS Collaboration, Search for associated production of dark matter with a Higgs boson decaying to \(\gamma\gamma\) or \(\gamma\gamma\) at \(\sqrt{s} = 13\) TeV, arXiv:1703.05236.


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

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

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

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

Louisiana Tech University, Ruston, Los Angeles, USA

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

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

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

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

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

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics and Astronomy, The University of Michigan, Ann Arbor, Michigan, USA

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

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

School of Physics, University of Minnesota, Minneapolis, Minnesota, USA

Department of Physics, McGill University, Montréal, Québec, Canada

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

Department of Physics, The University of New Mexico, Albuquerque, New Mexico, USA

Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

INFN Sezione di Milano, Italy

Dipartimento di Fisica, Università di Milano, Milano, Italy

INFN Sezione di Napoli, Italy

Dipartimento di Fisica, Università di Napoli, Napoli, Italy

Department of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

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

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

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

National Research Nuclear University MEPhI, Moscow, Russia

D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

INFN Sezione di Napoli, Italy

Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

Department of Physics, Northern Illinois University, DeKalb, Illinois, USA

Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

Department of Physics, New York University, New York, New York, USA

Ohio State University, Columbus, Ohio, USA

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA

Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA

Palacký University, RCPTM, Olomouc, Czech Republic

Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA

LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

Graduate School of Science, Osaka University, Osaka, Japan

Department of Physics, University of Oslo, Oslo, Norway

Department of Physics, Oxford University, United Kingdom

INFN Sezione di Pavia, Italy

Dipartimento di Fisica, Università di Pavia, Pavia, Italy

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA

National Research Centre “Kurchatov Institute” B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia

INFN Sezione di Pisa, Italy

Dipartimento di Fisica, Università di Pisa, Pisa, Italy

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal

Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

Department of Physics, University of Coimbra, Coimbra, Portugal

Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal

Departamento de Física, Universidade do Minho, Braga, Portugal
Department of Physics, University of Illinois, Urbana, Illinois, USA

Departamento de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain

Departamento de Física, University of British Columbia, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Faculty of Mathematics and Natural Sciences, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, Connecticut, USA

Yerevan Physics Institute, Yerevan, Armenia

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

Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, King’s College London, London, United Kingdom.

Department of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Department of Physics, Novosibirsk State University, Novosibirsk, Russia.

Also at TRIUMF, Vancouver, BC, Canada.

Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.

Also at Physics Department, An-Najah National University, Nablus, Palestine.

Also at Department of Physics, California State University, Fresno, CA, USA.

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.

Also at Departamento de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

Also at Departamento de Física e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.

Also at Tomsk State University, Tomsk, Russia.

Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPF), Canada.

Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at Borough of Manhattan Community College, City University of New York, New York City, USA.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

Also at Louisiana Tech University, Ruston, LA, USA.

Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

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

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Georgian Technical University (GTU), Tbilisi, Georgia.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Manhattan College, New York, NY, USA.

Also at Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile.

Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.

Also at The City College of New York, New York, NY, USA.

Also at School of Physics, Shandong University, Shandong, China.

Also at Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Portugal.

Also at Department of Physics, California State University, Sacramento, CA, USA.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Department de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.

Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.

Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

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

Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Department of Physics, Stanford University, Stanford, CA, USA.

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

Also at Giresun University, Faculty of Engineering, Turkey.

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

Also at Department of Physics, Nanjing University, Jiangsu, China.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.