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Search for dark matter in association with a Higgs boson decaying to b-quarks in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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ABSTRACT

A search for dark matter pair production in association with a Higgs boson decaying to a pair of bottom quarks is presented, using 3.2 fb^{-1} of pp collisions at a centre-of-mass energy of 13 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 backgrounds. Results are interpreted using a simplified model with a Z' gauge boson mediating the interaction between dark matter and the Standard Model as well as a two-Higgs-doublet model containing an additional Z' boson which decays to a Standard Model Higgs boson and a new pseudoscalar Higgs boson, the latter decaying into a pair of dark matter particles.

1. Introduction

Although dark matter (DM) constitutes the dominant component of matter in the universe, little is known about its properties and particle content [1]. The leading hypothesis suggests that most DM is in the form of stable, electrically neutral, massive particles with cosmological constraints indicating that DM interactions with Standard Model (SM) particles occur at a weak scale or below [2]. Collider-based searches for the particle content of DM provide important information complementary to that from direct and indirect detection experiments [3].

A traditional dark-matter signature at a proton–proton collider is one where one or more SM particles, X, are produced and detected, recoiling against missing transverse momentum – with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$ – associated with the non-interacting DM candidate. A number of searches at the Large Hadron Collider (LHC) [4] have been performed recently, where X is considered to be a hadronic jet [5,6], b- or t-quarks [7–9], a photon [10–13], or a W/Z boson [14–17]. The discovery of a Higgs boson, h [18,19], provides a new opportunity to search for DM production via the $h + E_{\mathrm{T}}^{\mathrm{miss}}$ signature [20–22]. In contrast to most of the aforementioned probes, Higgs boson radiation from an initial-state quark is Yukawa-suppressed. As a result, in a potential signal the Higgs boson would be part of the interaction producing the DM, providing unique insight into the structure of the DM coupling to SM particles. Recently, the ATLAS Collaboration has published such searches using 20.3 fb^{-1} of proton–proton collision data at $\sqrt{s} = 8$ TeV, exploiting the Higgs boson decays to two photons or a pair of bottom quarks [23,24].

This Letter presents an update on the search for $h + E_{\mathrm{T}}^{\mathrm{miss}}$, where the Higgs boson decays to a pair of bottom quarks ($h \to b\bar{b}$), using 3.2 fb^{-1} of pp collision data collected by the ATLAS detector at a centre-of-mass energy of 13 TeV during 2015. The results are interpreted in the context of simplified models of DM, characterised by a minimal particle content and the corresponding renormalisable interactions [25].

Many simplified models of DM production contain a massive particle which can be a vector, an axial-vector, a scalar or a pseudoscalar, and mediates the interaction between DM and Standard Model particles. In this search, simplified models involving a vector mediator are considered following the recommendation in Ref. [26].

In the first model [21], a vector mediator, Z', is exchanged in the s-channel, radiates the Higgs boson and decays into two DM particles. A diagram for this process is shown in Fig. 1(a). The vector mediator has an associated baryon number B, which is assumed to be gauge invariant under $U(1)_B$ thus allowing it to couple to quarks [27]. This symmetry is spontaneously broken to generate the Z' mass. However, there is no Z' coupling to leptons as such couplings are tightly constrained by dilepton searches. Finally, the dark-matter candidate carries a baryon number, which allows it to couple to quarks through the Z'. The parameters of this model are as follows: the coupling of Z' to dark matter (g_χ); the coupling of Z' to quarks (g_q); the coupling of Z' to the SM Higgs boson ($g_{Z'}$); the mixing angle between the baryonic Higgs boson, introduced in the model to generate the Z' mass, and the

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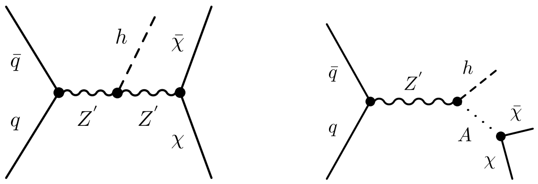

(a) (b)

Fig. 1. Diagrams showing the simplified models where (a) a Z' decays to a pair of DM candidates $\chi\bar{\chi}$ after emitting a Higgs boson h, and where (b) a Z' decays to a Higgs boson h and the pseudoscalar A of a two-Higgs-doublet model, and the latter decays to a pair of DM candidates $\chi\bar{\chi}$.

SM Higgs boson ($\sin\theta$); the Z' mass ($m_{Z'}$); and the DM particle mass (m_χ).

In the second model, apart from the vector mediator, the SM is extended by an additional Higgs field doublet, resulting in five physical Higgs bosons [22]: a light scalar h associated with the observed Higgs boson, a heavy scalar H, a pseudoscalar A, and two charged scalars $H^\pm$. The vector mediator is produced resonantly and decays as $Z' \to hA$ in a Type-II two-Higgs-doublet model (2HDM) [28]. The pseudoscalar A subsequently decays into two DM particles with a large branching ratio. A diagram for this process is shown in Fig. 1(b). To define the model, the ratio of the up- and down-type vacuum expectation values, $\tan\beta$, must be specified along with the Z' gauge coupling, g_Z, the DM particle mass, m_χ, and the Z' and A masses, $m_{Z'}$ and m_A, respectively. The results presented are for the alignment limit, in which the h–H mixing angle α is related to β by $\alpha = \beta - \pi/2$. Only regions of parameter space consistent with precision electroweak constraints [29] and with constraints from direct searches for dijet resonances [30–32] are considered. 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 if 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 $\tan\beta$.

2. ATLAS detector

ATLAS is a multi-purpose particle physics detector [33] at the LHC, with an approximately forward-backward symmetric and hermetic cylindrical geometry.[1] At its innermost part lies the inner detector (ID), immersed in a 2 T axial magnetic field provided by a thin superconducting solenoid, consisting of silicon pixel and microstrip detectors, which provide precision tracking in the pseudorapidity range $|\eta| < 2.5$. It is complemented by a transition radiation tracker providing tracking and particle identification information for $|\eta| < 2.0$. Between Run 1 and Run 2 of the LHC, the pixel detector was upgraded by the addition of a new innermost layer [34] that significantly improves the identification of heavy-flavour jets [35,36]. The solenoid is surrounded by sampling calorimeters: a lead/liquid-argon (LAr) electromagnetic calorimeter for $|\eta| < 3.2$ and a steel/scintillator tile hadronic calorimeter for $|\eta| < 1.7$. Additional LAr calorimeters with copper and tungsten absorbers provide coverage up to $|\eta| = 4.9$. In the outermost part, air-core toroids provide the magnetic field for the muon spectrometer. The latter consists of three layers of gaseous detectors: monitored drift tubes and cathode strip chambers for muon identification and momentum measurements for $|\eta| < 2.7$, and resistive-plate and thin-gap chambers for triggering up to $|\eta| = 2.4$. A two-level trigger system, custom hardware followed by a software-based level, is used to reduce the event rate to about 1 kHz for offline storage.

3. Data and simulation samples

The data sample used in this search, collected during normal operation of the detector, corresponds to an integrated luminosity of $3.2\,\text{fb}^{-1}$. The primary data sample is selected using a calorimeter-based E_T^miss trigger with a threshold of 70 GeV. The trigger efficiency for signal events selected by the offline analysis is about 90% for events with E_T^miss of 150 GeV and reaches 100% for events with E_T^miss larger than 200 GeV.

Signal samples are generated at tree level with MadGraph5_aMC@NLO 2.2.3 [37], interfaced to Pythia 8.186 [38] using the NNPDF2.3 parton distribution function (PDF) set [39] and the A14 parameter tune [40] for parton showering, hadronisation, underlying-event simulation, and for simulation of the Higgs boson decay to a pair of bottom quarks. For the vector-mediator simplified models, signals are generated with mediator mass between 10 and 2000 GeV and DM particle mass between 1 and 1000 GeV. The event kinematics are largely independent of the other parameters of the model, and thus the same values of these parameters are chosen following the recommendations in Ref. [26]: $g_\chi = 1.0$, $g_\text{q} = 1/3$, $g_{Z'} = m_{Z'}$, $\sin\theta = 0.3$. For the Z'-2HDM model, $pp \to Z' \to Ah \to \chi\bar{\chi}h$ samples are produced with Z' mass values between 600 and 1000 GeV, A mass values between 300 and 800 GeV (where kinematically allowed), and a DM mass value of 100 GeV. The other parameters chosen for this model are taken to be $\tan\beta = 1.0$ and $g_Z = 0.8$.

Higgs boson production in association with a W or Z vector boson, Vh, is modelled using Pythia 8.186 and the NNPDF2.3 PDF set. The samples are normalised using the SM total cross-sections calculated at next-to-leading order (NLO) [41] and next-to-next-to-leading order (NNLO) [42] in QCD for Wh and Zh, respectively, and include NLO electroweak corrections [43]. In all cases, the Higgs boson mass is set to 125 GeV.

Simulated samples of vector boson production in association with jets, $W/Z+$jets, where the W or Z bosons decay in all leptonic decay modes, are generated using Sherpa2.1.1 [44], including b- and c-quark mass effects, and the CT10 PDF set [45]. Matrix elements are calculated for up to two partons at NLO and four partons at LO using the Comix [46] and OpenLoops [47] matrix element generators and merged with the Sherpa parton shower [48] using the ME + PS@NLO prescription [49]. The cross-sections are determined at NNLO [50] in QCD. Furthermore, these backgrounds are split into different components according to the true flavour of the two jets that are used to identify the flavor of the reconstructed Higgs boson candidate, as described in Section 5: l denotes a light quark (u, d, s) or a gluon and the heavy quarks are denoted by c and b. This division is performed to allow accurate modelling of the $W/Z+$heavy-flavour backgrounds in the combined fit described in Section 8.

Diboson production modes, including ZZ, WW, and WZ processes, with one boson decaying hadronically and the other leptonically are simulated using the Sherpa2.1.1 generator with the CT10 PDF set. They are calculated for up to one (ZZ) or zero (WW/WZ) additional partons at NLO and up to three additional partons at LO using the Comix and OpenLoops matrix element generators and merged with the Sherpa parton shower using the ME + PS@NLO

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points towards the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ is the azimuthal angle around the beam pipe. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle. Finally, the angular distance ΔR is defined as $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$.

prescription. Their cross-sections are determined by the generator at NLO.

The $t\bar{t}$ and single-top-quark backgrounds are generated with PowhegBox [51] using the CT10 PDF set. It is interfaced with Pythia 6.428 [52] to simulate parton showering, fragmentation, and the underlying event, for which the CTEQ6L1 PDF set [53] and the Perugia 2012 parameter tune [54] are used. The $t\bar{t}$ cross-section is determined at NNLO in QCD and next-to-next-to-leading logarithms (NNLL) for soft gluon radiation [55], while the single-top-quark cross-sections are fixed to those in Refs. [56–58]. A top-quark mass of 172.5 GeV is used throughout.

The simulated event samples are processed with the detailed ATLAS detector simulation [59] based on Geant4 [60]. Effects of multiple proton–proton interactions (pile-up) as a function of the instantaneous luminosity are taken into account by overlaying simulated minimum-bias events generated with Pythia8.186 with the A2 tune [61] and MSTW2008LO PDF set [62] onto the hard-scattering process, such that the distribution of the average number of interactions per bunch crossing in the simulated event samples matches that in the data.

4. Object reconstruction

Proton–proton collision vertices are reconstructed using ID tracks with $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$. The primary vertex is defined as the vertex with the highest $\Sigma (p_{\mathrm{T}}^{\mathrm{track}})^2$. Each event is required to have at least one vertex reconstructed from at least two tracks.

Muon candidates are identified by matching tracks found in the ID to either full tracks or track segments reconstructed in the muon spectrometer, and are required to satisfy the *loose* muon identification quality criteria [63]. Electron candidates are identified as ID tracks that are matched to a cluster of energy in the electromagnetic calorimeter. Electron candidates must satisfy a likelihood-based identification requirement [64] based on shower shape and track selection criteria, and are selected using the *loose* working point. Both the muons and electrons are required to originate from the primary vertex, to have $p_{\mathrm{T}} > 7\,\mathrm{GeV}$, and to lie within $|\eta| < 2.5$ for muons and $|\eta| < 2.47$ for electrons. They are further required to be isolated using requirements on the sum of p_{T} of the tracks within a cone around the lepton direction. The cone size and the requirements are varied as a function of the lepton p_{T} to obtain an efficiency that is fixed as a function of p_{T} such that a 99% efficiency for prompt leptons is retained across a broad kinematic range.

Jets are reconstructed in two categories, small-radius (small-R) and large-radius (large-R) jets. In both cases, the jets are reconstructed from topological clusters of calorimeter cells using the anti-k_t jet clustering algorithm [65]. In the case of small-R jets, a radius parameter of $R = 0.4$ is used and the effects of pile-up are corrected for by a technique based on jet area [66]. In the case of large-R jets, a radius parameter of $R = 1.0$ is used and the jet trimming algorithm [67,68] is applied to minimise the impact of energy depositions due to pile-up and the underlying event. This algorithm reconstructs subjets within the large-R jet using the k_{t} algorithm [69] with radius parameter $R_{\mathrm{sub}} = 0.2$ and removes any subjet with p_{T} less than 5% of the large-R jet p_{T}. The jet energy scale, and also in the case of large-R jets the jet mass scale, is calibrated using p_{T}- and η-dependent factors determined from simulation, with small-R jets receiving further calibrations using *in situ* measurements [70]. Small-R jets within the ID acceptance, $|\eta| < 2.5$, are called *central* in the following and are required to satisfy $p_{\mathrm{T}} > 20\,\mathrm{GeV}$. Those with $2.5 < |\eta| < 4.5$ are called *forward* and are required to satisfy $p_{\mathrm{T}} > 30\,\mathrm{GeV}$. To reduce the effects of pile-up in small-R jets with $p_{\mathrm{T}} < 50\,\mathrm{GeV}$ and $|\eta| < 2.5$, a significant fraction of the tracks associated with each jet must have an origin compatible with the primary vertex, as defined by the jet vertex tagger [71]. Furthermore, small-R jets are removed if they are within a $\Delta R = 0.2$ cone around an electron candidate. Large-R jets are required to satisfy $p_{\mathrm{T}} > 250\,\mathrm{GeV}$ and $|\eta| < 2.0$.

Track jets are built from tracks using the anti-k_t algorithm with $R = 0.2$. Track jets with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.5$ are selected and are matched by ghost-association [72] to large-R jets. Small-R jets and track jets containing b-hadrons are identified – "b-tagged" – using a boosted decision tree that combines information about the impact parameter and reconstructed secondary vertices of the tracks associated with these jets [35,36,73]. A working point is used which achieves an average efficiency of 70% in identifying small-R calorimeter jet (track jet) containing a b-hadron with misidentification probabilities of $\sim$12 (18)% for charm-quark jets and $\sim$0.2 (0.6)% for light-flavour jets, as determined in a simulated sample of $t\bar{t}$ events. Track jets have higher misidentification probabilities due to the smaller radius parameter used.

The missing transverse momentum, $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$, is defined as the negative vector sum of the transverse momenta of the calibrated physics objects (electrons, muons, small-R jets), with unassociated energy depositions, referred to as the soft-term, accounted for using ID tracks with $p_{\mathrm{T}} > 0.5$ GeV [74,75]. Furthermore, a track-based missing transverse momentum vector, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, is calculated as the negative vector sum of the transverse momenta of tracks with $|\eta| < 2.5$, consistent with originating from the primary vertex.[2]

5. Event selection

For an event to be considered in the search, it is required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 150\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$, and no identified, isolated muons or electrons. This is referred to as the *zero-lepton region*.

Events with $E_{\mathrm{T}}^{\mathrm{miss}}$ less than 500 GeV are considered in the *resolved region*. First, this set of events is required to have at least two central small-R jets. Following this selection, the reconstructed small-R jets are ranked as follows. First, the central jets are divided into two categories, those that are b-tagged and those that are not. Each of these samples of jets are ordered in decreasing p_{T}. The ordered set of b-tagged jets is considered with the highest priority, while those that are central but not b-tagged are considered with second priority, and finally any forward jets, ordered in decreasing p_{T}, are considered last. The two most highly ranked jets are used to reconstruct the Higgs boson candidate, h_{r}, and therefore cannot contain forward jets. Furthermore, at least one of the jets constituting h_{r} must satisfy $p_{\mathrm{T}} > 45\,\mathrm{GeV}$. Finally, events are divided into three categories based on the number of central jets that are b-tagged being either zero, one, or two b-tagged central jets. To achieve a high $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency, events are retained if the scalar sum of the p_{T} of the three leading jets is greater than 150 GeV. This requirement is lowered to 120 GeV if only two central small-R jets are present.

Additional selections are applied to further suppress the multijet background. Specifically, to reject events with $E_{\mathrm{T}}^{\mathrm{miss}}$ due to mismeasured jets a requirement is placed on the minimum azimuthal angle between the direction of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and each of the jets, $\min\left(\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}\right)\right) > 20°$, for the three highest-ranked jets. Furthermore, the azimuthal angle between the $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, $\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$, is required to be less than 90°, to suppress events with misreconstructed missing transverse momentum. The Higgs boson candidate is required to be well separated

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[2] Throughout this search, the magnitude of $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$ and the magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is referred to as $p_{\mathrm{T}}^{\mathrm{miss}}$. Only when the directionality is necessary does the notation use the vector symbol.

in azimuth from the missing transverse momentum by requiring $\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, h_{\mathrm{r}}\right) > 120°$. Finally, to reject back-to-back dijet production, the azimuthal opening angle of the two jets forming the Higgs boson candidate is required to be $\Delta\phi\left(j^1_{h_{\mathrm{r}}}, j^2_{h_{\mathrm{r}}}\right) < 140°$.

The DM signal is expected to have large $E_{\mathrm{T}}^{\mathrm{miss}}$, whereas the background is expected to be most prominent at low $E_{\mathrm{T}}^{\mathrm{miss}}$. Therefore, to retain signal efficiency while preserving the increased sensitivity of the high $E_{\mathrm{T}}^{\mathrm{miss}}$ region, events in the resolved region are separated into three categories based on the reconstructed $E_{\mathrm{T}}^{\mathrm{miss}}$: 150–200 GeV, 200–350 GeV, and 350–500 GeV.

In the *merged region* – composed of events with $E_{\mathrm{T}}^{\mathrm{miss}}$ in excess of 500 GeV – the presence of at least one large-R jet is required, associated with at least two track jets [76], and the highest p_{T} large-R jet is taken as the reconstructed Higgs candidate. In an analogous way to the resolved region, the events are classified based on the number of b-tagged track jets associated with the large-R jet into three categories with zero, one, and two or more b-tags.

The combined selection of both the resolved and merged selections in the signal region with two or more b-tags yields a signal acceptance times efficiency ranging between 5 and 30%. The primary change in the signal acceptance is due to the choice of masses (e.g. $m_{Z'}$ and m_A) in the point of parameter space being probed.

The search is performed by implementing a shape fit of the reconstructed dijet mass (m_{jj}) or single large-R jet mass (m_{J}) distribution. After event selection, the energy calibration of the b-tagged jets is improved as follows. The invariant mass of the candidate is corrected [77] if a muon is identified within $\Delta R = 0.4$ of a b-tagged small-R jet, or within $\Delta R = 1.0$ of the large-R jet. The four-momentum of the closest muon in ΔR within a jet is added to the calorimeter-based jet energy after removing the energy deposited in the calorimeter by the muon (muon-in-jet correction). Additionally, a simulation-based jet-p_{T}-dependent correction [77] is applied in the case of b-tagged small-R jets to improve the signal resolution of the reconstructed Higgs mass peak. Events consistent with a DM signal would have a reconstructed mass near the Higgs boson mass, thereby allowing the sidebands to act as a natural control region to further constrain the backgrounds estimated from dedicated $W/Z+$jets and $t\bar{t}$ control regions and the multijet estimates described in Section 6.

6. Background estimation

The background is mainly composed of SM $W/Z+$jets and $t\bar{t}$ events, which constitute 15–65% and 45–80% of the total background, respectively, depending on the $E_{\mathrm{T}}^{\mathrm{miss}}$ value. The model for these backgrounds is constrained using two dedicated control regions. Other backgrounds, including diboson, Vh, and single top-quark production, constitute less than 15% of the total background and the estimation is modelled using simulated event samples. The contribution from multijet events arises mainly from events containing jets containing semi-muonic decays of b-hadrons. It constitutes less than 2% of the background in the resolved region and is negligibly small in the merged region, and is estimated using a data-driven technique.

In addition to the zero-lepton region, which serves as a control region to constrain the $Z+$jets background in the zero-b-tag case and via the reconstructed mass sidebands that enter in the fit as described in Section 8, two dedicated control regions are used to constrain the main $W/Z+$jets and $t\bar{t}$ backgrounds. These control regions are defined based on the number of leptons and b-tags in the event and are orthogonal to each other and to the signal region.

The *one-muon control region* is designed to constrain the $W+$jets and $t\bar{t}$ backgrounds. Events are selected using the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and are required to have exactly one muon candidate and no electron candidates. Furthermore, the full signal region selection is applied after modifying the $E_{\mathrm{T}}^{\mathrm{miss}}$ observable to mimic the behaviour of such events that contaminate the signal region by adding the p_{T} of the reconstructed muon to the $E_{\mathrm{T}}^{\mathrm{miss}}$. As in the signal region, these events are divided into exclusive regions based on the number of b-tags. This division naturally separates $t\bar{t}$ from $W+$jet events.

The *two-lepton control region* is used to constrain the $Z+$jets background contribution. Events are collected using a single-electron or single-muon trigger and selected by requiring exactly one electron pair or muon pair. Of these two leptons, one is required to have $p_{\mathrm{T}} > 25$ GeV. The electron (muon) pair must have an invariant mass $83 < m_{\ell\ell} < 99$ GeV ($71 < m_{\ell\ell} < 106$ GeV). In the muon channel, where a larger mass window is used, an opposite-charge requirement is also applied. Furthermore, the missing transverse momentum significance, defined as the ratio of $E_{\mathrm{T}}^{\mathrm{miss}}$ to the square root of the scalar sum of lepton and jet p_{T} in the event, is required to be less than $3.5\,\mathrm{GeV}^{1/2}$ in order to reject $t\bar{t}$ background. In this control region, the transverse momentum of the dilepton system, p_{T}^{V}, is used – instead of $E_{\mathrm{T}}^{\mathrm{miss}}$ – to match the division of the resolved and merged regions and the categorisation of the resolved events. Other than the above, the event selection and Higgs boson candidate requirements are the same as in the signal region.

The multijet background for the resolved analysis is determined using a data-driven method. A sample of events selected to satisfy the analysis trigger, $p_{\mathrm{T}}^{\mathrm{miss}}$ requirement, and inverted $\min(\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}))$ requirement, is used to provide multijet templates of all the distributions relevant to the analysis. These templates are normalised by a fit to the distribution of the number of small-R jets that contain a muon in the nominal selection. The fit is performed separately for each b-tag category. Since agreement is found between the categories the average normalisation scale factor is used. In the merged region, it was found that the requirement of high $E_{\mathrm{T}}^{\mathrm{miss}}$ suppresses the multijet background to a negligible level. Therefore it is not included as a background in the search.

7. Systematic uncertainties

The most important experimental systematic uncertainties arise from the determination of the b-tagging efficiency and mistag rate, the luminosity determination and uncertainties associated with the calibration of the scale and resolution of the jet energy and mass. The uncertainties in the small-R jet energy scale have contributions from *in situ* calibration studies, from the dependence on pile-up activity and on flavour composition of jets, and from the changes of the detector and run conditions between Run 1 and Run 2 [78,79]. The uncertainty in the scale and resolution of large-R jet energy and mass are evaluated by comparing the ratio of calorimeter-based to track-based measurements in dijet data and simulation [80]. The b-tagging efficiency uncertainty arises mainly from the uncertainty in the measurement of the efficiency in $t\bar{t}$ events [73,81].

Other experimental systematic uncertainties with a smaller impact are those in the lepton energy and momentum scales, and lepton identification and trigger efficiencies [63,82,83]. An uncertainty in the $E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale is taken into account [74], and uncertainties due to the lepton energy scales and resolutions, as well as reconstruction and identification efficiencies, are also considered, although they are negligible. The uncertainty in the integrated luminosity amounts to 2.1%, and is derived following a methodology similar to that detailed in Ref. [84].

Uncertainties are also taken into account for possible differences between data and the simulation modelling used for each process. The SHERPA $W+$jets and $Z+$jets background modelling is studied in the one and two lepton control regions, respectively, as a function of p_T of the vector boson, the mass m_jj or m_J and the azimuthal angle difference $\Delta\phi_\mathrm{jj}$ between the small-R jets used to reconstruct the Higgs in the resolved region. The shape of the data distributions is described by the simulation with no indication that a correction is needed. A shape uncertainty in these variables is derived, encompassing the data/simulation differences. An uncertainty in the SHERPA description of the flavour composition of the jets in these backgrounds is derived by comparing to MadGraph. The top-quark background modelling is studied in the dedicated one lepton control region, and in a two lepton control region using $e\mu$ pairs. Both the p_T and mass of the two small-R jet system are studied. A systematic uncertainty is derived based on the data/simulation comparison in these regions.

The normalisations of the $W+b\bar{b}$, $Z+b\bar{b}$, and $t\bar{t}$ contributions are determined directly from the data by leaving them as free parameters in the combined fit. The normalisations of the other $W/Z+$jets background contributions are obtained from theory predictions, with assigned normalisation uncertainties of 10% for $W/Z+l$, 30% for $W/Z+cl$ and a 30% uncertainty is applied to the relative normalisation between $W/Z+bc/bl/cc$ to $W/Z+b\bar{b}$. In addition, the following normalisation uncertainties are assigned to the background processes: 4% for single-top in the s- and t-channels, 7% for single-top in the Wt-channel [85,86], and 50% for associated $(W/Z)h$ [77,87] production. The sources of uncertainty considered for the cross-sections for the diboson production (WW, WZ and ZZ) are the renormalisation and factorisation scales, the choice of PDFs and parton-shower and hadronisation model. The multijet contribution is estimated from data and is assigned a 50% uncertainty. Uncertainties arising from the size of the simulated event sample are also taken into account.

Uncertainties in the signal acceptance from the choice of PDFs, from the choice of factorisation and renormalisation scales, and from the choice of parton-shower and underlying-event tune have been taken into account in the analysis. These are typically $<10\%$ each, although they can be larger for regions with low acceptance at either low or high $E_\mathrm{T}^\mathrm{miss}$ depending on the model and the choice of masses. In addition, uncertainties arising from the limited number of simulated events have been taken into account.

The contribution of the various sources of uncertainty for an example production scenario is given in Table 1.

Table 1
The percentage impact of the various sources of uncertainty on the expected production cross-section for the signal in the vector-mediator model with $m_{Z'}=2000$ GeV and $m_\chi=1$ GeV, normalised to a cross section of 0.1 pb.

Source of uncertainty	Impact [%]
Total	23.0
Statistical	20.5
Systematic	10.3
Experimental uncertainties	
b-tagging	6.6
Luminosity	4.4
Jets $+E_\mathrm{T}^\mathrm{miss}$	2.8
Leptons	0.4
Theoretical and modelling uncertainties	
Top	5.1
$Z+$jets	3.4
Signal	2.6
$W+$jets	1.5
Diboson	0.6
Multijet	0.5
Vh $(h\to b\bar{b})$	0.4

8. Results

Results are extracted by means of a profile likelihood fit to the reconstructed invariant mass distribution of the dijet system or single-large-R-jet simultaneously in all signal and control regions. The normalisations of the major backgrounds are constrained by the data in both the signal and control regions. The shapes of the background distributions are taken from Monte Carlo simulations but can be modified within the systematic errors listed in Section 7. The spectra entering the fit are those from the three selections associated with the number of leptons with each of these regions divided into three categories based on the number of b-tags and four kinematic regions. In the zero-lepton region, this division is based on $E_\mathrm{T}^\mathrm{miss}$ while in the one- and two-lepton regions, it is based on $p_\mathrm{T}(\mu, E_\mathrm{T}^\mathrm{miss})$ and $p_\mathrm{T}(\ell,\ell)$, respectively. The shape information is not used in the zero-b-tag distributions in order to simplify the fit. This division is designed to isolate, and more effectively constrain, different backgrounds. In particular, the $Z+$jets background normalisation is constrained both by the sample of events containing two leptons and those containing zero leptons and zero b-tags. In addition, the set of events containing one lepton and zero b-tags constrains the $W+$jets normalisation while those containing one or two b-tags constrain both the $W+$jets and $t\bar{t}$ normalisations. The parameter of interest in the fit is the signal yield, while all parameters describing the systematic uncertainties and their correlations are included in the likelihood function as nuisance parameters, with Gaussian constraints, implemented using the framework described in Refs. [88,89]. The nuisance parameters with the largest effect on the determination of the parameter of interest are the flavour-tagging and jet systematic uncertainties, together with the normalisation of the $t\bar{t}$ and $W+b\bar{b}$ backgrounds. The reconstructed Higgs boson candidate mass distribution is shown in Fig. 2 in each of the $E_\mathrm{T}^\mathrm{miss}$ categories for the set of events with two b-tags with the integrated event yields shown in Table 2. Furthermore, shown in Fig. 3 is the $E_\mathrm{T}^\mathrm{miss}$ distribution in the signal region, noting that in the two portions of the spectrum, below and above $E_\mathrm{T}^\mathrm{miss}=500$ GeV, the requirements on the hadronic activity are taken from the small-R and large-R jets, respectively. No significant excess of events is observed above the background, with the global significance of the deviation of the data from the background-only prediction being 0.056.

Upper limits on the production cross-section for the process times branching ratio of the Higgs boson decaying to two bottom quarks $(\sigma(pp\to h\chi\chi)\times \mathrm{BR}(h\to b\bar{b}))$ are set at 95% confidence level using the CL_s modified frequentist formalism [90] with the profile-likelihood-ratio test statistic [91]. For the Z'-2HDM model, these limits range from 191.3 fb for a Z' mass of 600 GeV and an A mass of 300 GeV to 6.72 fb for a Z' mass of 1600 GeV and an A mass of 600 GeV. For the vector mediator model interpretation, the limits range from 1.01 pb for a mediator mass of 50 GeV and a dark matter mass of 1 GeV to 40.3 fb for a mediator mass of 800 GeV and a dark matter mass of 500 GeV. These are further interpreted as lower limits on the mass parameters of interest in the specific model. In Fig. 4(a) the Z'-2HDM exclusion contour in the $(m_{Z'}, m_A)$ plane for $\tan\beta=1$, $m_\chi=100$ GeV is presented, with limits more stringent than obtained in Run 1, excluding Z' masses up to 1950 GeV and A masses up to 500 GeV. In Fig. 4(b), the exclusion contour is shown in the $(m_{Z'}, m_\chi)$ plane for the vector mediator model described in Section 3. This interpretation was not performed in Run 1 and the mass reach for this choice of couplings excludes Z' masses below 700 GeV for low DM mass.

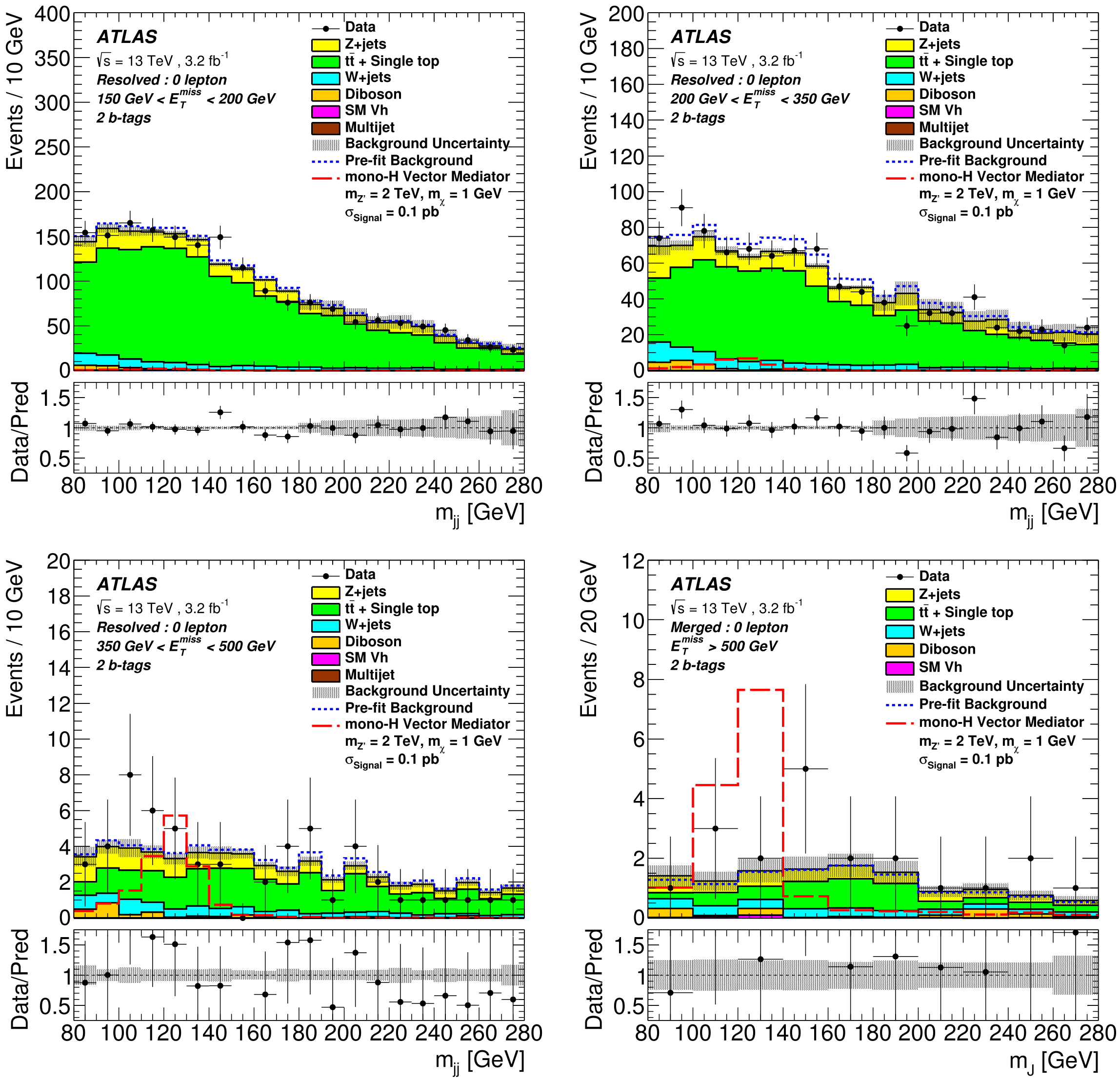

Fig. 2. The reconstructed dijet and single jet invariant mass distribution in the resolved and the merged signal regions for the case where two b-tags have been identified for the four kinematic regions. The Standard Model background expectation is shown before (after) the profile likelihood fit by the dashed blue line (solid histograms) with the bottom panel showing the ratio of the data to the predicted background after the combined fit with no signal included. For visual clarity the various components of the $W/Z+$jets ($b\bar{b}$, bc, bl, $c\bar{c}$, cl, ll) backgrounds have been merged and labelled $W+$jets and $Z+$jets. The expected signal in the vector-mediator model with $m_{Z'}=2$ TeV and $m_\chi=1$ GeV, normalised with a cross-section of 0.1 pb, is also shown. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

Table 2
The numbers of predicted background events following the profile likelihood fit for each background process, the sum of all background components, and observed data yields in the two b-tag signal region of the resolved and merged channels for each E_T^{miss} region. Statistical and systematic uncertainties are combined. The uncertainties in the total background take into account the correlation of systematic uncertainties among different background processes. The expected signal in the vector-mediator model with $m_{Z'}=2000$ GeV and $m_\chi=1$ GeV.

E_T^{miss} [GeV]	Resolved			Merged
	150–200	200–350	350–500	>500
$Z+$jets	259 ± 27	171 ± 13	14.6 ± 1.2	3.80 ± 0.44
$W+$jets	95 ± 28	70 ± 22	7.5 ± 2.4	2.48 ± 0.71
$t\bar{t}$ & Single top	1444 ± 44	656 ± 25	30.8 ± 1.4	4.9 ± 0.9
Multijet	21 ± 10	11.0 ± 5.0	0.58 ± 0.27	–
Diboson	17.8 ± 1.6	18.7 ± 1.0	2.53 ± 0.22	1.20 ± 0.12
SM Vh	2.8 ± 1.3	2.8 ± 1.4	0.46 ± 0.23	0.15 ± 0.08
Total Bkg.	1840 ± 33	930 ± 20	56.5 ± 2.1	12.5 ± 1.3
Data	1830	942	56	20
Exp. Signal	8.0 ± 0.8	24.5 ± 1.8	16.1 ± 1.2	14.9 ± 3.4

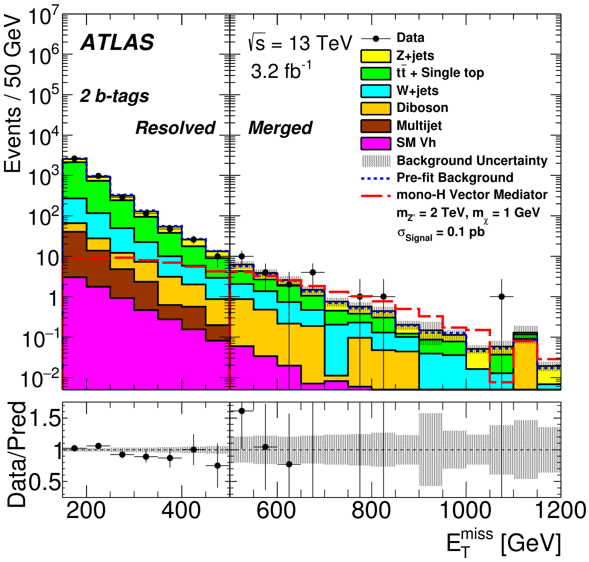

Fig. 3. The reconstructed $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the combined resolved and merged two-b-tag signal regions. The Standard Model prediction is shown before (after) the profile likelihood fit by the dashed blue line (solid histograms) with the bottom panel showing the ratio of the data to the predicted background after the combined fit with no signal included. For visual clarity the various components of the $W/Z+$ jets (bb, bc, bl, cc, cl, ll) backgrounds have been merged and labelled $W+$jets and $Z+$jets. The multijet background is found to be negligible in the merged region. The expected signal in the vector-mediator model with $m_{Z'} = 2$ TeV and $m_\chi = 1$ GeV, normalised with a cross-section of 0.1 pb, is also shown.

9. Conclusion

A search is presented for dark-matter pair production in association with a Higgs boson decaying into two b-quarks, using 3.2 fb^{-1} of pp collisions collected at $\sqrt{s} = 13$ TeV by the ATLAS detector at the LHC. Two regions are considered, a low-$E_{\mathrm{T}}^{\mathrm{miss}}$ region where the two b-quark jets from the Higgs boson decay are reconstructed separately and a high-$E_{\mathrm{T}}^{\mathrm{miss}}$ region where they are reconstructed inside a single large-radius trimmed jet.

The data are found to be consistent with the background expectation and the results are interpreted for two simplified models involving a massive vector mediator. In the Z'-two-Higgs-doublet, constraints are placed on the $(m_{Z'}, m_A)$ space and found to exclude a wide range of Z' masses with the pseudo-scalar Higgs mass exclusion reaching up to 500 GeV. In the context of the vector mediator model, constraints are placed in the two-dimensional space of $(m_{Z'}, m_\chi)$ and found to exclude vector mediators with masses up to 700 GeV.

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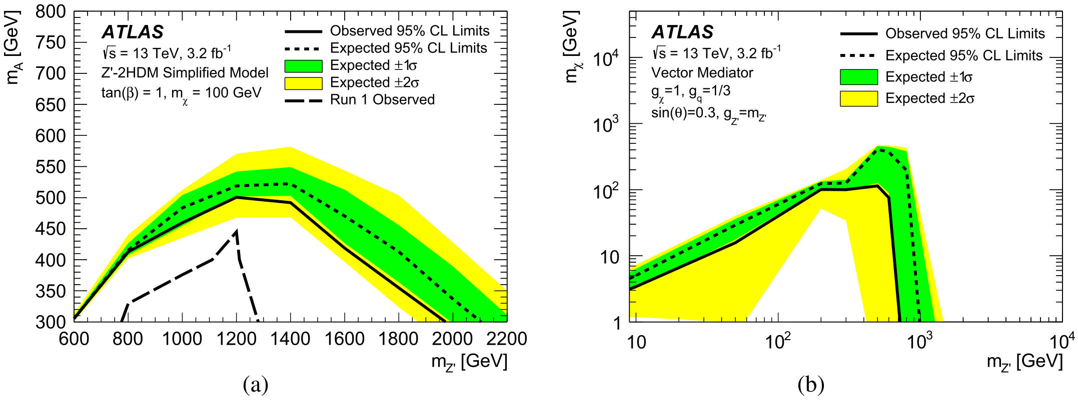

(a) (b)

Fig. 4. Exclusion contours for (a) the Z'-2HDM in the $(m_{Z'}, m_A)$ plane for $\tan\beta = 1$ and $m_\chi = 100$ GeV and (b) the vector-mediator model in the $(m_{Z'}, m_\chi)$ plane for $\sin\theta = 0.3$, $g_\chi = 1$, $g_q = 1/3$ and $g_{Z'} = m_{Z'}$. The expected limits are given by the dashed lines, while the green and yellow bands indicate the $\pm1\sigma$ and $\pm2\sigma$ uncertainty bands, respectively. The observed limits are given by the solid lines. The parameter space below the limit contours are excluded at 95% confidence level. Shown for the Z'-2HDM exclusion is the observed limit from the Run 1 search while no such exclusion is shown from Run 1 for the vector-mediator model as it was not used for interpretation in the Run 1 ATLAS search. (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

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