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# Search for Dark Matter produced in association with a Higgs boson decaying to $b\bar{b}$ at $\sqrt{s}$=13 TeV using 36.1 fb$^{-1}$ with the ATLAS detector

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The search for events with large missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) recoiling against a Standard Model (SM) particle is a probe for detecting Dark Matter (DM) at the LHC. The discovery of the Higgs boson $h$ opens a new opportunity through the $h$+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature, with $h \to b\bar{b}$ being the most probable decay channel. The results are interpreted in the context of a simplified model ($Z'$-2HDM) which describes the interaction of DM and SM particles through new heavy mediator particles. The analysis of data recorded by the ATLAS detector using 36.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s}$=13 TeV is presented here, together with an highlight on the new techniques that will be adopted in the near future to extend the search including the data collected during 2017.

*Sixth Annual Conference on Large Hadron Collider Physics (LHCP2018)*
*4-9 June 2018*
*Bologna, Italy*

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PoS(LHCP2018)014

## 1. Introduction

One of the outstanding questions that cannot be answered by the SM, whose success has been established by the discovery of the Higgs boson in 2012 [1, 2], is related to the unknown nature of the DM [3]. A compelling hypothesis that accommodates the observed relic abundance of DM [4, 5] is the existence of an electrically neutral stable particle $\chi$ with additional weak interaction with the SM particles, beyond gravity, and a mass in the range of a few GeV up to several TeV.

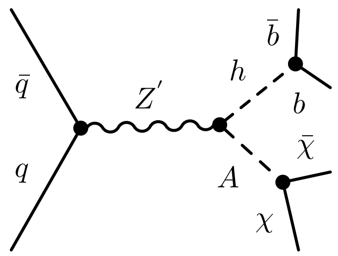
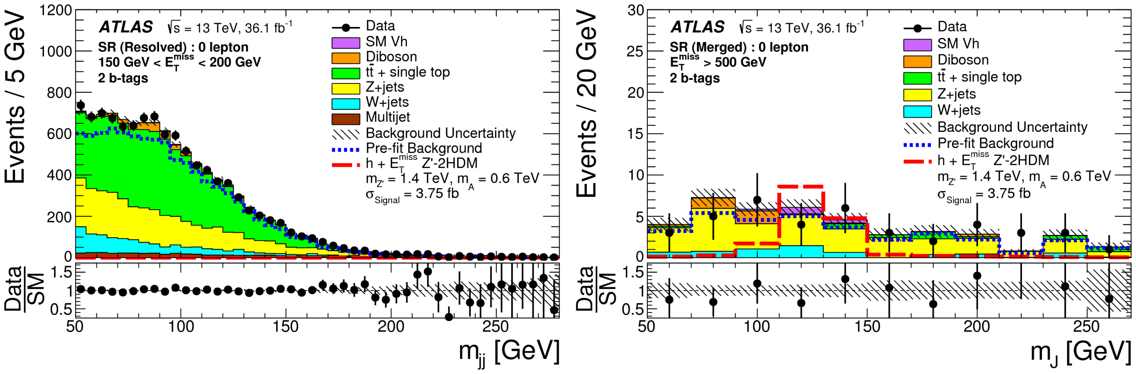



Figure 1: The leading-order contribution of the production of DM and a Higgs boson through a new $Z'$ mediator coupled to a pseudo-scalar Higgs boson $A$, where the latter decays primarily to $\chi\bar{\chi}$.

The typical signature targeted by collider searches is the pair production of DM particles, recoiling against a visible object $X$, leading to a large amount of $E_{\mathrm{T}}^{\mathrm{miss}}$. Compared to other searches where the object $X$ originates from initial state radiation, the $h$+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature allows to directly probe the hard interaction involving the DM particles. The signal model used in the interpretation of the results is a Type-II two-Higgs-doublet model (2HDM) with an additional U$(1)_{Z'}$ gauge symmetry, referred to as $Z'$-2HDM [6]. Among the five physical Higgs bosons resulting from this model is one light scalar $h$ that is identified with the SM Higgs boson and a pseudo-scalar $A$. The process yielding the signature of $h$+DM is $pp \to Z' \to Ah$, with the subsequent decay of $A$ into $\chi\bar{\chi}$, as illustrated in Figure 1. The relevant model parameters are therefore the masses of the involved particles, $m_A$, $m_{Z'}$, $m_\chi$ , as well as the gauge coupling of the $Z'$, $g_{Z'}$, and $\tan\beta$, which denotes the ratio of the vacuum expectation values of the two Higgs fields coupling to the up- and down-type quarks.

## 2. Analysis strategy

Depending on the magnitude of the transverse momentum of the Higgs boson (and hence $E_{\mathrm{T}}^{\mathrm{miss}}$), the events are divided in two different categories: *resolved* region ($E_{\mathrm{T}}^{\mathrm{miss}} \leqslant$500 GeV) and *merged* region ($E_{\mathrm{T}}^{\mathrm{miss}}$>500 GeV). The Higgs candidate is reconstructed as a system of two small radius (small-$R$) calorimeter jets, in the resolved region, and as a single large radius (large-$R$) jet containing two subjets, in the merged region. Jets containing $b$-hadrons ($b$-jets) are identified with an algorithm based on multivariate techniques [7], referred to as $b$-tagging. This search employs the `MV2c10` $b$-tagging discriminant. Small-$R$ jets are reconstructed using the anti-$k_t$ algorithm [8] with a radius parameter of 0.4 from topological clusters of energy deposits in the calorimeter [9]. Large-$R$ jets are reconstructed using the anti-$k_t$ algorithm with a radius parameter of 1.0. In order to reduce the contamination from pile-up and underlying events, the jets are groomed using the trimming procedure as described in Ref. [10]. The identification of the flavour content of the large-$R$ jet is based on track jets ghost-associated [11] with the ungroomed jet. The track jets are reconstructed from Inner Detector (ID) tracks using the anti-$k_t$ algorithm with a radius parameter of 0.2. The reconstruction of muons ($\mu$) is performed using the information from the muon spectrometer and the matched ID tracks, while electrons ($e$) are reconstructed by matching an ID track to a cluster of energy in the calorimeter. Lastly, the $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated as the negative vector sum of the transverse momenta of $e$, $\mu$ and jet candidates in the event. The search is performed using in total four $E_{\mathrm{T}}^{\mathrm{miss}}$ bins (150-200, 200-350, 350-500, $>$ 500). The Signal Region (SR) is characterised by the presence of high $E_{\mathrm{T}}^{\mathrm{miss}}$ and no isolated $e$ or $\mu$. In order to estimate the contribution of the main backgrounds ($Z(\nu\nu)$+jets, $W$+jets and $t\bar{t}$), two different Control Regions (CRs) are used: the 1-$\mu$ CR is used to constrain the $W$+jets and $t\bar{t}$ processes, while 2-$l$ CR ($l$=$e$,$\mu$) is used to constrain the $Z$+jets contribution. Events in the SR and in the 1-$\mu$ CR are required to pass the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger, while events in 2-$l$ CR are collected using a single-lepton trigger. In order to distinguish the $W$+jets and $t\bar{t}$ contributions, in the 1-$\mu$ CR the muon charge is used as most discriminant variable, while the dijet or leading large-$R$ jet mass is used in the SR and in the 2-$l$ CR. A simultaneous profile-likelihood fit [12, 13] to the CRs and SRs is performed to constrain the backgrounds or extract information about the potential presence of a signal, respectively. The post-fit distributions of the Higgs candidate mass are presented in Figure 2 in the SR with two $b$-tags, showing that no excess is observed over SM prediction [6].



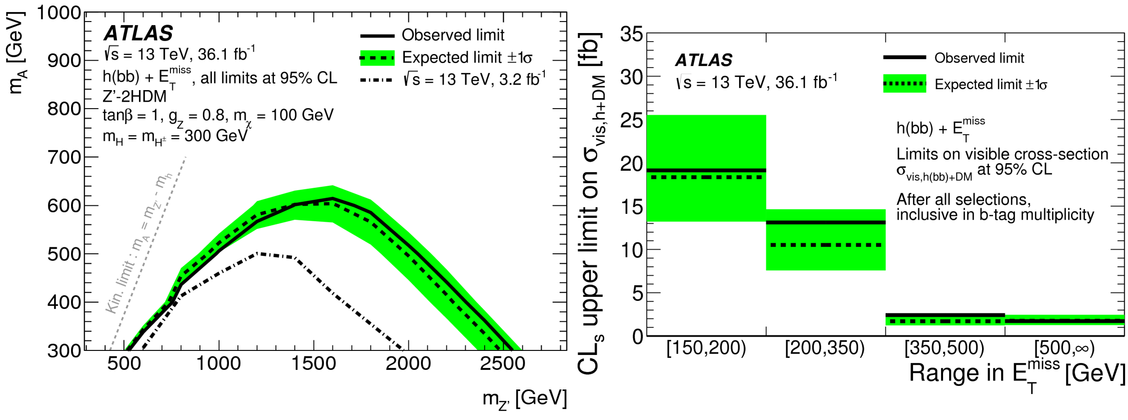

(a) (b)

Figure 2: Post-fit SR distributions of the dijet invariant mass in the lowest $E_{\mathrm{T}}^{\mathrm{miss}}$ bin (on the left) and leading large-R jet mass in the merged region (on the right).

## 3. Results and future improvements

The results are interpreted as exclusion limits at 95% confidence level (CL) on the production cross-section for $h \to b\bar{b}$+DM events. Exclusion contours in the ($m_{Z'}$,$m_A$) space are shown in Figure 3a [6]. Values of $m_{Z'}$ up to 2.6 TeV and $m_A$ up to 0.6 TeV are therefore excluded. Moreover, less model-dependent limits on the visible cross-section for $h \to b\bar{b}$+DM events, obtained analysing one $E_{\mathrm{T}}^{\mathrm{miss}}$ bin at a time, are derived and shown in Figure 3b [6].

The sensitivity of this search relies heavily on the ability to identify both jets from the Higgs decay as $b$-jets since this is a powerful mean of background suppression. However, at very high energy, when reconstructed with standard algorithms using a fixed radius parameter, these jets cannot always be resolved [14]. A rather immediate solution is given by the usage, in the merged region, of Variable-Radius (VR) track jets, whose radius parameter decreases with the jet $p_{\mathrm{T}}$ [15, 16]. As shown in Figure 4, the VR track jets have found to outperform the R=0.2 technique and are therefore expected to greatly improve the sensitivity of this search at high $E_{\mathrm{T}}^{\mathrm{miss}}$.




(a) (b)

Figure 3: Exclusion contours in the ($m_{Z'}$,$m_A$) for the $Z'$-2HDM signal model (on the left) and less model-dependent upper limits on the visible cross-section for $h \to b\bar{b}$+DM events (on the right).

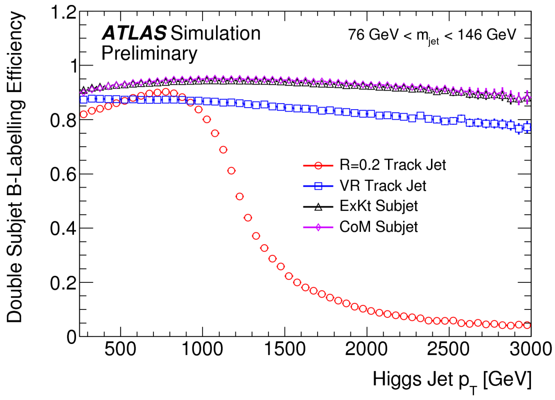



Figure 4: The efficiency for a Higgs jet to have its two leading associated subjets matched to truth b-hadrons vs Higgs jet $p_{\mathrm{T}}$. Figure taken from Ref. [17].

## 4. Conclusions

A search for DM produced in association with a Higgs boson decaying to $b\bar{b}$ has been presented, 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 has been excluded. Limits are also placed on the production cross-section of non-SM events without extra model assumptions. The analysis of the extended dataset, including the data collected during 2017, is expected to largely improve the sensitivity of this search by using VR track jets in the merged region for $b$-tagging, overcoming the current limitation due to jet merging at high energy.

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