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Search for Dark Matter produced in association with a Standard Model Higgs Boson decaying to b-quarks with the ATLAS detector

Anindya Ghosh[a]

[a] *The University Of Arizona, 1118 E. Fourth Street, Tucson, USA*

E-mail: anindya.ghosh@cern.ch

The Standard Model (SM) of particle physics has been immensely successful in explaining elementary particles and how they interact with each other. However, SM alone is insufficient to answer many open questions in modern physics, such as the presence of dark matter (DM) and dark energy (DE) in our universe. Ordinary matter, observed so far by various experiments, accounts for only about 5% of the energy density of the universe, while a large fraction is in the form of DM (~27%) and DE (~68%). While the nature of DM is still unknown, one of the leading hypotheses suggests that it consists of Weakly Interacting Massive Particles (WIMP). All evidence point to the interaction between DM and SM to be very weak. DM searches are being pursued in collider experiments alongside direct and indirect detection experiments. Since the DM particles would interact very weakly with the detector they would escape undetected. This will induce a momentum imbalance in the transverse plane of the plane where interactions are taking place, also known as the missing transverse energy (E_T^{miss}). Since at the LHC the E_T^{miss} can only be evaluated in the presence of visible SM particles, the DM searches are performed in association with SM particles that can be detected at the LHC. In this document, a search for dark matter candidates produced in association with a Standard Model Higgs boson decaying to two b-jets is presented. The search uses a dataset of pp collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 139 fb^{-1}, recorded by the ATLAS detector. The results are interpreted in the context of the Two-Higgs Doublet Model (2HDM) with an additional vector or pseudoscalar mediator. The 2HDM is connected to the so-called Higgs portal models, in which DM particles interact with the SM particles only through their couplings with the Higgs sector. The analysis did not discover any DM particles and constraints are put on the model parameters. Some parts of the benchmark DM model phase-space are excluded and improvements are observed compared to previous results.

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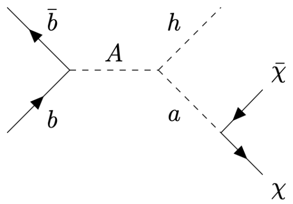
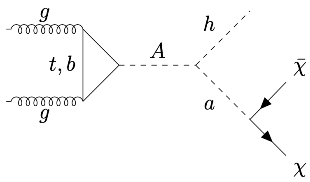
The analysis targets events with final states consisting of E_T^{miss} coming from the undetected DM particles and two b-jets from the SM Higgs decay. This is commonly known as the mono-Higgs channel. The results are interpreted in terms of the Two-Higgs Doublet Models (2HDM) [1, 2]. A statistical analysis based on a binned profile-likelihood method is performed to obtain the final results. The 2HDM model is derived by extending the SM with an additional Higgs doublet resulting in 5 Higges: two neutral CP-even H and h, one neutral CP-odd A, and two charged Higgs bosons $H^{\pm}$. The model analyzed in this search is based on a gauge-invariant and renormalisable 2HDM+a model, which is an extension of the 2HDM. Here an additional pseudoscalar singlet P is incorporated along with the two Higgs doublets. The pseudoscalar a is a superposition of the CP-odd components of the two Higgs doublets and P, mediating the interactions between the Higgs sector and the invisible DM candidates (χ). The 2HDM+a model produces a $h + \chi\bar{\chi}$ final state, where A decays to a SM Higgs h and a pseudoscalar a, followed by a subsequent decay of the pseudoscalar to DM particle χ ($a \to \chi\bar{\chi}$). There are two production mechanisms corresponding to the $h + \chi\bar{\chi}$ final state: (i) bb initiated process, and (ii) gluon-gluon fusion (ggF) process, as shown in Figure 1. The cross sections for the ggF and bb-induced models are dependent on the choice of tanβ (the ratio of the vacuum expectation values of the two Higgs doublets). The ggF mechanism is dominant for low tanβ, while the bb-induced mechanism is dominant for high tan β regions. For the benchmark models considered in this thesis, tan β = 1 (ggF dominant) and tan β = 10 (bb dominant) are chosen. Both the processes have similar cross sections for tan β ~5 [1].



(a) 2HDM+a bb mode

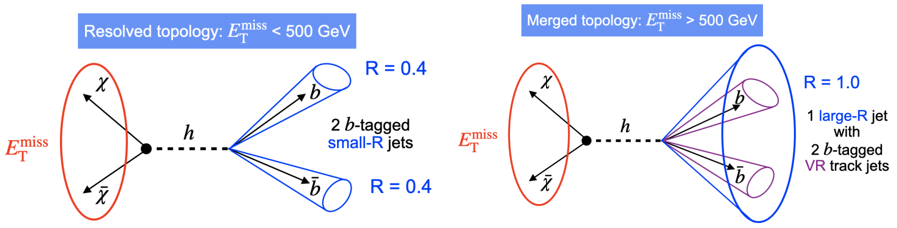


(b) 2HDM+a ggF mode

Figure 1: Feynman diagrams of bb-initiated (fig. 1a) and ggF (fig. 1b) production mechanisms in 2HDM+a model with $h + \chi\bar{\chi}$ final state.

The analysis targets events with a final state consisting of E_T^{miss} originating from the undetected DM particles ($a \to \chi\chi$) and two b-jets from the Higgs boson decay ($h \to bb$) i.e. 0-lepton signal region (SR): $E_T^{\text{miss}} + h \to bb$. The SM Higgs boson is reconstructed from the b-tagged jets, and the reconstruction procedure depends on the SM Higgs boson p_t. For low p_t Higgs, the two b-jets can be identified separately, and the Higgs candidate is reconstructed with two central ($|\ \eta\ | < 2.5$) small-R (R=0.4) b-tagged jets. However, for highly boosted Higgs bosons, the b-jets get collimated and it becomes difficult to distinguish the two b-jets separately. In these scenarios, the Higgs candidate is reconstructed with a large-R jet (R=1.0) with two associated b-tagged Variable Radius (VR) track jets. For this reason, the analysis phase space is divided into two topologies: *Resolved* and *Merged* (c.f 2). Since the Higgs p_t is correlated to the E_T^{miss}, the E_T^{miss} is used as the discriminating variable to define the Resolved and Merged topologies, Resolved: $150 < E_T^{\text{miss}} < 500$ GeV and Merged: $E_T^{\text{miss}} > 500$ GeV. The major backgrounds in the analysis are: semi-leptonic top-pair decay ($t\bar{t} \to bW^+\ \bar{b}W^- \to b\ell^+\nu\ \bar{b}q\bar{q}$), and $W^{\pm}/Z$ bosons produced in association with jets. A 1-lepton control region (CR) containing exactly one muon (μ^+/μ^-) is defined to estimate the $t\bar{t}$ and $W^{\pm}$+

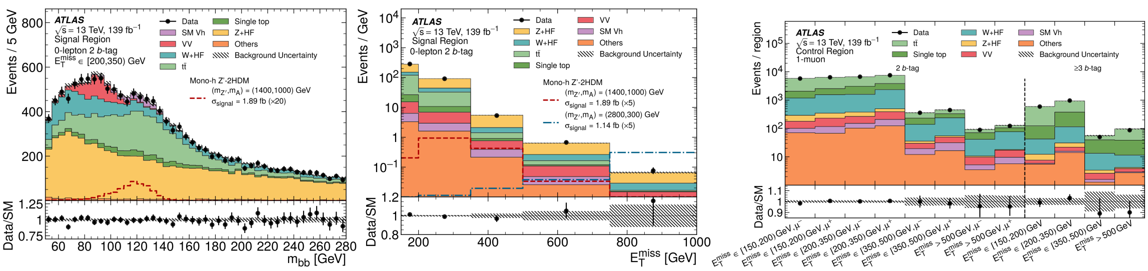
jets backgrounds. Also two 2-lepton CRs with exactly two leptons that can be either two opposite flavor electrons (e^+e^-) or muons ($\mu^+\mu^-$) are constructed to estimate the Z+jets backgrounds. To gain sensitivity to the different 2HDM+a production modes the analysis phase space is divided into different b tag categories: $2b$ and $\geq 3b$ tagged regions. Each region is further binned into E_T^{miss} bins to gain sensitivity to a wide A, a mass range (m_A, m_a): Resolved topology: E_T^{miss} = [150-200, 200-350, 350-500] GeV for $2b$ and $\geq 3b$ tagged, Merged topology: E_T^{miss} = [500-750, >750] GeV for $2b$, and E_T^{miss} >500 GeV for $\geq 3b$ tagged.



(a) Resolved topology **(b)** Merged topology

Figure 2: Figures show the Resolved (*left*) and Merged (*right*) topologies of the mono-$h(bb)$ analysis phase space.

The statistical interpretation of the observed data, in the context of a possible mono-$h(bb)$ DM signal, is performed with a profile likelihood (PL) fit where the SR and CRs are fitted simultaneously. The fit discriminant used in the SR is the Higgs candidate mass distribution (m_{bb}). As shown in figures 3a- 3c, no significant data excess from SM predictions is observed. Upper limits on the signal cross sections are derived to obtain exclusion limits on the (m_A, m_a) plane.



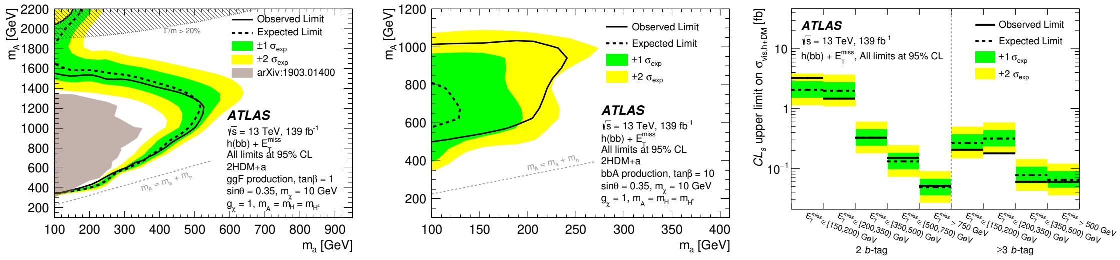
(a) m_h in $2b$ E_T^{miss} (200-350) GeV SR **(b)** E_T^{miss} in $2b$ SR **(c)** E_T^{miss} in CR

Figure 3: Figures show the post-fit data-MC comparisons for m_{bb} and E_T^{miss} distributions in different analysis regions [3]. The agreement between data and MC is withing the uncertainty bands.

Figures 4a- 4c show the exclusion contours at a 95% CL for the 2HDM+a ggF, 2HDM+a bb-induced and model-independent upper limits on visible cross sections respectively, where the signal points under the curves are excluded. For the 2HDM+a ggF signal model the exclusion limit(4a) reaches up to m_A = 1.25 TeV for m_a = 520 GeV. The gray area represents the exclusion contour results obtained from the analysis with 36 fb^{-1} [4] ATLAS data, and as shown in Figure 4a the improvement for the exclusion contour is up to 180 GeV for m_a. The exclusion limits go higher for low m_a, high m_A regions due to the increase of $a \to ah$ cross-section. As shown in Figure 4b, the exclusion limit for the 2HDM+a bb-induced model reaches up to m_A = 900 GeV for m_a = 240

GeV. Due to the inclusion of the ≥ 3 b-tag regions the analysis gained sensitivity for the 2HDM+a bb-induced model, which was not the case in the previous analyses. The 2HDM+a bb-induced model is sensitive to much smaller phase space in (m_A, m_a) plane. This is because the 2HDM+a bb-induced model has much lower acceptance compared to the 2HDM+a ggF model and the number of signal events in the ≥ 3 b-tag regions passing $E_T^{\text{miss}} > 150$ GeV selection is significantly fewer.

The results can also be interpreted with a minimal assumption that a $b\bar{b}$ resonance is produced with a mass close to the SM Higgs boson mass $m_h = 125$ GeV in association with a significant E_T^{miss}. This is also known as the model-independent limit (MIL) and model-independent upper limits are obtained on the visible cross-section (effective cross-section visible to the detector which is a fraction of the total cross-section). Figure 4c shows the MIL limits across different analysis regions.



(a) 2HDM+a ggF **(b)** 2HDM+a bb **(c)** Model independent limits

Figure 4: 2HDM+a exclusion limits on $m_A - m_a$ planes for bb(4b) and ggF(4a) modes, and model independent limits on the visible cross-section(4c) [3, 4].

References

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