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Searches for Dark Matter with the ATLAS Experiment at the LHC

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The presence of a non-baryonic Dark Matter (DM) component in the Universe is inferred from the observation of its gravitational interaction. If Dark Matter interacts weakly with the Standard Model (SM) it could be produced at the LHC. The ATLAS Collaboration has developed a broad search program for DM candidates in final states with large missing transverse momentum produced in association with other SM particles (light and heavy quarks, photons, Z and h bosons, as well as additional heavy scalar particles) and searches where the Higgs boson provides a portal to Dark Matter, leading to invisible Higgs decays. The results of recent searches on 13 TeV pp data from the LHC, their interplay and interpretation are discussed.

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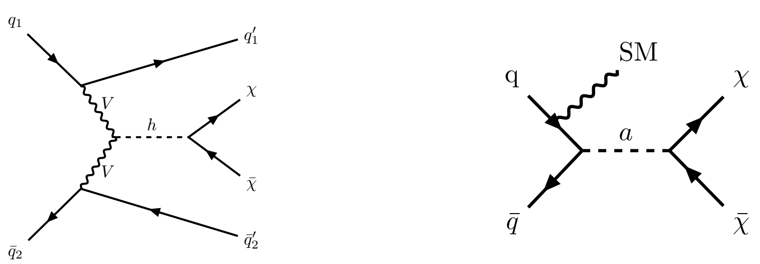
There is plenty of astrophysical evidence for a non-baryonic, mainly gravitationally interacting matter [1–3], called "Dark Matter" (DM). The Standard Model (SM) does not account for this matter. Multiple avenues of detecting Dark Matter are explored, among others to produce Dark Matter in the collision of SM particles at particle colliders. The ATLAS Experiment [4] is one of the two multipurpose particle detectors at the world's most powerful particle collider, the Large Hadron Collider (LHC), and therefore perfectly suited to search for Dark Matter.

A particularly promising class of candidates for Dark Matter are weakly interacting massive particles (WIMPs, [5]). At the LHC, WIMP particles χ could be produced in the decay of either the SM Higgs boson h or a beyond-the-Standard-Model (BSM) mediator particle, as shown in Figure 1. Due to their inherently small interaction cross section with ordinary matter, WIMP particles χ produced in proton–proton collisions would leave the ATLAS detector without interacting. They manifest as missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, due to energy conservation in the transverse plane if additional detector-visible objects are in the events. Recently, the ATLAS collaboration measured an upper limit of 0.107 (0.077 expected) at the 95 % confidence level for the branching fraction of invisible decays of the SM Higgs boson [6]. Complementary, final states in which different detector-visible objects recoil against large $E_{\mathrm{T}}^{\mathrm{miss}}$ from the escaping DM particles were studied (see e.g. Refs. [7–11]), called *mono-X* searches. An example Feynman diagram is shown in Figure 1b. Detector-visible objects taken into consideration were, among others, jets, (B)SM bosons as well as top quarks. Three of them shall be specifically highlighted in the following, all of which use approximately 140 fb^{-1} of ATLAS Run-2 data at a centre-of-mass energy $\sqrt{s} = 13$ TeV.

A search for a new leptonically decaying neutral vector boson Z' produced in association with $E_{\mathrm{T}}^{\mathrm{miss}}$ is presented in Ref. [11]. This search is, among others, inspired by dark-Higgs models [12]. In these, a new neutral vector boson Z' radiates an invisibly decaying dark Higgs boson h_D and decays to leptons ℓ afterwards, $pp \to Z' \to Z'(\ell^+\ell^-)h_D(\chi\bar{\chi})$. The event selection of the search for these events is a prototypical example for mono-X searches. Most importantly, the search requires events to have an opposite-sign di-muon or di-electron pair with an invariant mass well above that of the Standard-Model Z boson, $m_{\ell\ell} > 180$ GeV. Further, large missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV, is required. A search for resonances in the invariant mass distribution $m_{\ell\ell}$ is performed. The data is found to be in good agreement with the SM expectation. In consequence, exclusion limits among others on dark-Higgs models are set. For this model, cross section times branching fractions for $Z'(\ell^+\ell^-)\chi\bar{\chi}$ down to $2 \cdot 10^{-5}$ are excluded at 95 % confidence level.



(a) **(b)**

Figure 1: Example Feynman diagrams for (a) a SM Higgs boson h and (b) a BSM mediator a decaying to Dark Matter χ. In (b) the whole process is invisible to the detector if no SM particle is radiated.

Given that searches for simpler final states like the one discussed above have continuously led to null results in the past, increasingly complex objects and final states are investigated in ATLAS mono-X searches. An example is given by the search for Dark Matter produced in association with a Higgs boson decaying to tau leptons [9]. This search is inspired by a two-Higgs-doublet model with a pseudoscalar mediator a to Dark Matter (2HDM+a, [13]). The main selected process is a heavy pseudoscalar A that decays to an invisibly decaying mediator to Dark Matter a and a SM Higgs boson h that decays to tau leptons, $pp \to A \to h(\tau^+\tau^-)a(\chi\bar{\chi})$. In this search, tau leptons are required in the final state, contrary to Ref. [11] which required electrons or muons. Tau leptons are significantly more difficult to reconstruct because they decay before reaching the subdetectors of the ATLAS Experiment. For this reason, hadronically decaying tau leptons are reconstructed using a recurrent neural network. The event selection of the search requires two opposite-charge tau leptons and $E_{\mathrm{T}}^{\mathrm{miss}} > 150\,\mathrm{GeV}$. The data is found to be in good agreement with the SM expectation. Therefore, model-independent exclusion limits as well as exclusion limits on the 2HDM+a are set. For the latter, masses of the pseudoscalar a up to 300 GeV are excluded at 95 % confidence level.

Finally, the search for Dark Matter produced in association with a single top quark and an energetic W boson shall be highlighted [10]. This search is also inspired by the 2HDM+a and targets events for example from the decay of a charged Higgs boson $H^\pm$, $pp \to tH^\pm \to tW^\pm a(\chi\bar{\chi})$. The event selection requires $E_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ and a bottom-quark tagged jet from the top-quark decay. The search makes use of three different channels linked to the decay of the two W bosons in the event. In the 0-lepton channel, no leptons, at least four small-radius jets and at least one W-tagged large-radius jet are required in the event. In the 1-lepton channel, exactly one electron or muon and at least two small-radius jets are required. The 2-lepton channel is obtained from a previous publication [14]. All three channels are orthogonal because of the required lepton multiplicity and are statistically combined. The data is found to be in good agreement with the SM expectation. Therefore, model-independent exclusion limits as well as exclusion limits on the 2HDM+a are set. For the latter, masses of the pseudoscalar a up to 350 GeV are excluded at 95 % confidence level.

To provide an overview of the various ATLAS searches sensitive to the 2HDM+a, a summary of the exclusion limits was assembled [15]. The summary takes into account a statistical combination of three mono-X searches and overlays the exclusion limits from up to 14 other ATLAS searches, among others from the $h(\tau^+\tau^-) + E_{\mathrm{T}}^{\mathrm{miss}}$ and $tW + E_{\mathrm{T}}^{\mathrm{miss}}$ searches discussed above. An example can be found in Figure 2. The figure gives the observed (expected) exclusion limits from the different searches as solid (dashed) lines. There are two main exclusion regions. On the one hand, mono-X searches dominantly exclude a region that is driven by the production and decay of s-channel resonances as shown in Figure 2b. On the other hand, searches that do not require large $E_{\mathrm{T}}^{\mathrm{miss}}$ in the final state, for example for charged Higgs bosons as shown in Figure 2c, give exclusion limits independent of the mass of the mediator to Dark Matter a. Overall, masses up to $m_a = 560\,\mathrm{GeV}$ at $m_A = 1200\,\mathrm{GeV}$ as well as masses $m_A < 700\,\mathrm{GeV}$ independent of m_a are excluded.

In summary, the analysis of LHC Run-2 data recorded with ATLAS is coming to an end. A multitude of different searches for WIMP Dark Matter has been performed. Thereby, more and more intricate final states and methods, e.g., involving tau leptons or W tagging, respectively, are being investigated. Combinations, for example for the 2HDM+a or the branching fraction of invisible Higgs decays, have been published to form the ATLAS Run-2 legacy. In 2022, the LHC Run 3

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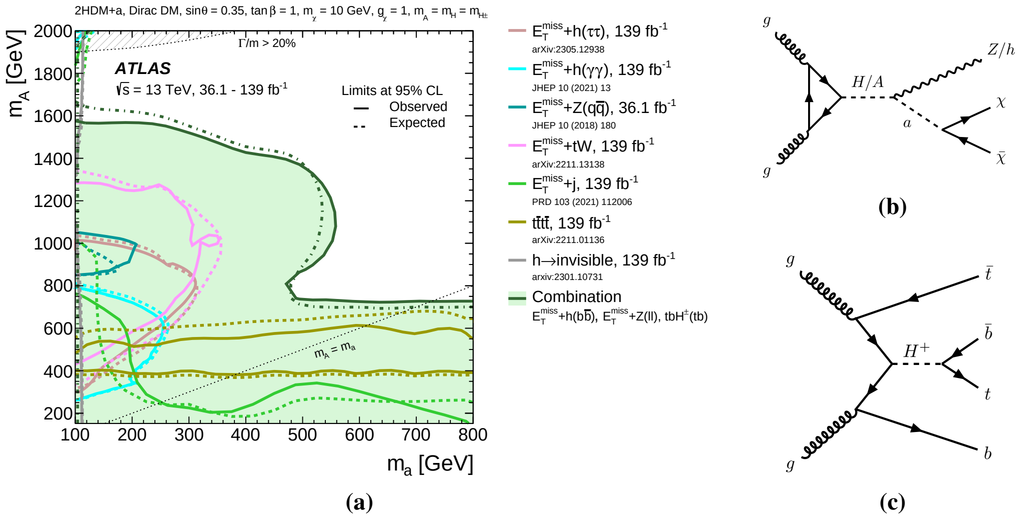

Figure 2: (a) ATLAS summary for the 2HDM+a exclusion limits in the $(m_a, m_H \equiv m_A \equiv m_{H^\pm})$ plane. The observed (expected) exclusion regions at 95 % confidence are marked by solid (dashed) lines. The dashed grey area indicates the region where the width of at least one BSM Higgs boson is larger than 20 % of its mass. Figure taken from Ref. [15]. (b) Feynman diagram for s-channel resonances decaying to a SM boson and a DM pair. (c) Feynman diagram for DM-free final states with charged-Higgs production.

started, providing even more integrated luminosity. Consequently, future ATLAS searches for Dark Matter will exhibit further reduced statistical uncertainties and more innovative methods.

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