Searches for exotic Dark Matter at ATLAS and CMS

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The nature of dark matter (DM) is still a mystery. Many direct and indirect search experiments are trying to solve this puzzle. The LHC offers a unique opportunity at the high energy frontier, where DM particles or related new particles may be produced. Both the CMS and ATLAS collaborations have carried out comprehensive DM search programs, providing critical missing pieces to the puzzle. In this article, recent exotic DM searches in CMS and ATLAS are summarized and a brief outlook is given.

1 Introduction

The nature of dark matter (DM) remains a mystery and there are many Beyond Standard Model (BSM) theories proposed to provide an explanation. The Large Hadron Collider (LHC) [1] offers a unique opportunity to search for DM and related new particles at the high energy frontier. ATLAS [3] and CMS [2] are the two general-purpose detectors at the LHC that are capable of searching for new particles using a large set of experimental signatures. Both experiments have carried out comprehensive dedicated DM search programs.

The full LHC Run 2 data brings higher sensitivities to inclusive DM searches such as the mono-jet, mono-Z and mono-Higgs searches. More final states are being explored with the help of innovative analysis techniques, motivated by theories such as dark Higgs [4] and dark photon [5]. The theoretical framework has also advanced in the past decade, taking previous experimental results into account. As a consequence, more BSM models have been proposed that are now considered in both CMS and ATLAS. In particular, the 2HDM+a model [6] is widely considered in recent searches. Figure 1 shows the diagrams of the models mentioned above.

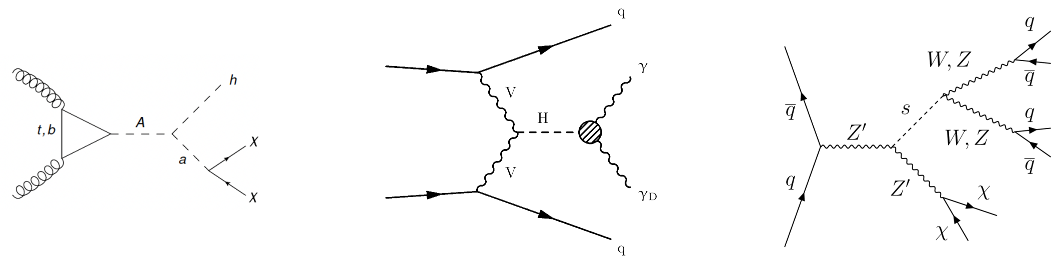

Figure 1 – Diagrams of various models considered in recent DM searches. Left: A Higgs boson is produced in association with a pseudo-scalar (a) decaying to DM candidates; middle: a Higgs boson is produced in the VHF channel, decaying to a photon and a dark photon; right: a dark Higgs s is produced in association with a Z', where the Z' decays to DM candidates and the dark Higgs decays to two vector bosons.

Recent results from both CMS and ATLAS will be summarized in the next section, followed by an outlook on the future DM search programs at the LHC. All searches discussed in this article use full Run 2 dataset.

2 Dedicated search results

2.1 Mono-X searches

The mono-jet search is the flagship analysis in the DM search program as its final state covers a large range of the parameter space and is sensitive to many different models. The recent ATLAS mono-jet search [7] uses data collected by a missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}}$, trigger. The events are required to have at least one energetic jet and not have leptons or photons present.

Signal regions are divided by $E_{\mathrm{T}}^{\mathrm{miss}}$ and various control regions are constructed by allowing leptons. A simultaneous fit is performed in both the signal regions and control regions, and the resulting discriminant spectrum expected from the background is compared with data to determine whether there are significant deviations in the latter. This simultaneous fit strategy is a common procedure adopted by all the searches discussed in this article.

The mono-Z search is also a very important inclusive analysis. The recent CMS mono-Z search [8] considers the leptonic final state where the Z boson decays to either a pair of muons or electrons. Events are collected by di-muon (di-electron) triggers and must contain two well-identified, isolated muons (electrons) with the same flavor and opposite charge, forming an invariant mass compatible with the Z boson mass. Events with additional leptons, more than one jet or any b-tagged jets are vetoed to suppress the backgrounds. Signal regions are constructed based on either the missing transverse momentum, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, or the transverse mass between the di-lepton system and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, m_{T}. The latter region is optimized for 2HDM+a model as there is a peak in m_{T} spectrum near the neutral scalar (H) mass.

Both the mono-jet and mono-Z searches have results compatible with the background estimations, and upper limits are set on specific models as the examples shown in Figure 2.

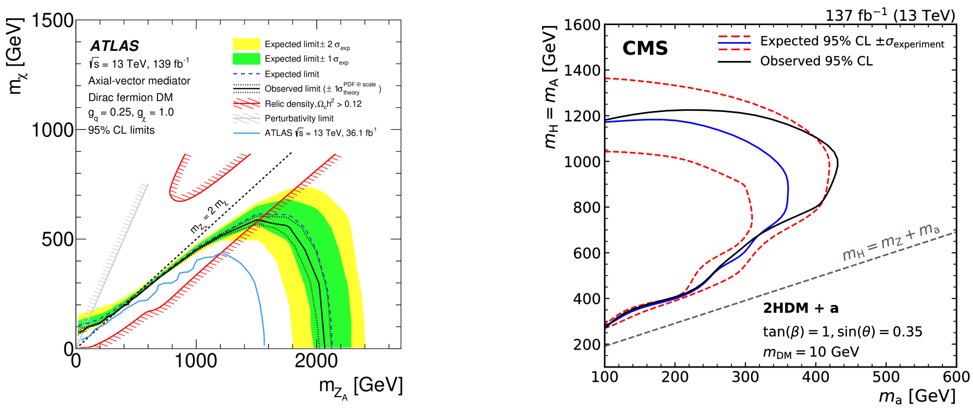

Figure 2 – Left: observed (solid) and expected (dashed) limits on the axial-vector mediator masses obtained in the mono-jet search [7]. The y-axis corresponds to the dark matter mass (m_χ) while the x-axis refers to the axial-vector mass ($m_{Z_{\mathrm{A}}}$). Right: observed (solid) and expected (dashed) limits on the 2HDM+a model obtained in the mono-Z search [8]. The y-axis corresponds to the neutral scalar mass (m_{H}) while the x-axis refers to the pseudo-scalar mass (m_{a}).

Both the mono-jet and mono-Z search consider well known detectable standard model (SM) physic objects. Searches considering less well known SM particles, such as the Higgs boson or new BSM particles such as new scalar particles target particular phase space, face different experimental challenges. The recent ATLAS mono-Higgs($\to b\bar{b}$) search [9] analyzes events collected by the primary $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers. Events are required to have a significant $E_{\mathrm{T}}^{\mathrm{miss}}$ above the trigger threshold and not contain isolated leptons. The signal regions are categorized by the b-tagged jet multiplicity (two or three) and the collinearity of the two b-tagged jets forming the Higgs candidate. The "resolved" category considers two well separated calorimeter jets and the "merged" category considers two nearby variable radius track jets. The ATLAS mono-s($\to VV$) search [10] probes a similar final state but looks for hadronic boson decays instead of b-hadron decays. Events must contain two boson-tagged jets, and the signal regions are categorized by their collinearity as well.

Results agree well with the background expectation in both the mono-Higgs($\to b\bar{b}$) and mono-s($\to VV$) searches. Upper limits are set on specific models as the examples shown in Figure 3.

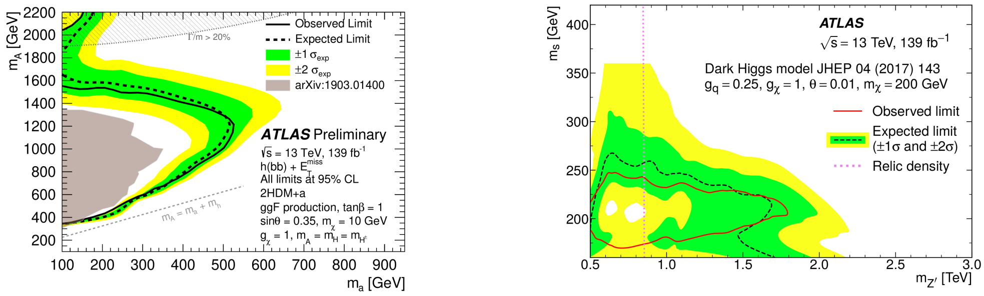

Figure 3 – Left: observed (solid) and expected (dashed) limits on the 2HDM+a model obtained in the mono-H($\to b\bar{b}$) search [9]. The y-axis corresponds to the heavy Higgs boson mass (m_{A}) and the x-axis refers to the pseudo-scalar mass m_{a}. Right: observed (solid) and expected (dashed) limits on the dark Higgs model obtained in the mono-s($\to VV$) search [10]. The y-axis corresponds to the dark Higgs boson mass (m_{s}) and the x-axis refers to the Z' mass $m_{Z'}$.

2.2 Dark photon search in the vector boson fusion (VBF) channel

As the most recently discovered SM particle, the Higgs boson opens up an interesting avenue for DM search, not only because it can be produced in association with DM particles, but also it may decay to DM particles. The invisible Higgs decay branching ratio is a critical channel to study the phase space where $m_{\mathrm{DM}} < \frac{1}{2}m_{\mathrm{H}}$. The invisible Higgs decay branching ratio measurement [11] sets a stringent upper limit of 0.11 at 95% CL. Recent ATLAS [13] and CMS [12] searches explore another unique scenario where the Higgs boson decays to a dark photon and a photon, which gives a significant $E_{\mathrm{T}}^{\mathrm{miss}}$ and a photon in the final state. Both searches consider the VBF production channel given its larger cross section, applying similar event selections such as containing VBF jets and lepton veto. The m_{T} between the photon and the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is used as the discriminant variable to define the signal regions.

No significant deviations are observed in both searches and upper limits are set on $\sigma_{\mathrm{VBF}} \times B(H \to \gamma + inv)$ as shown in Figure 4. It is worth mentioning that ATLAS applies a lower photon p_{T} threshold and additional jet centrality requirements, resulting in stronger exclusion limits.

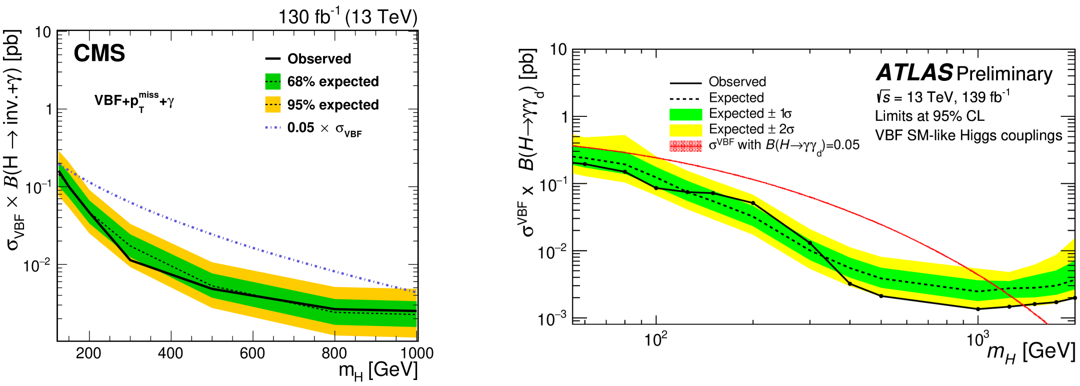

Figure 4 – Observed (solid) and expected (dashed) limits on $\sigma_{\mathrm{VBF}} \times B(H \to \gamma + inv)$ obtained in the CMS [12] (left) and ATLAS [13] (right) search. The x-axis refers to the Higgs boson mass (m_{H}).

2.3 DM interpretations in SUSY searches

R-parity conserving (RPC) SUSY predicts a stable lightest supersymmetric particle (LSP), which is a good DM candidate. SUSY searches targeting this scenario usually requires large $E_{\mathrm{T}}^{\mathrm{miss}}$ and high jet (b-tagged jet) multiplicity. Certain DM models share similar final states. In a recent ATLAS SUSY search [14], dedicated signal regions are constructed and optimized for DM particles produced in association with a pair of b-quarks. Event selections include $E_{\mathrm{T}}^{\mathrm{miss}}$, b-jet multiplicity and lepton veto. In addition, specialized variables exploring the angular correlations are applied to optimize individual signal regions. The background prediction agrees well with the data, therefore upper limits are set on the DM production cross section as shown in Figure 5.

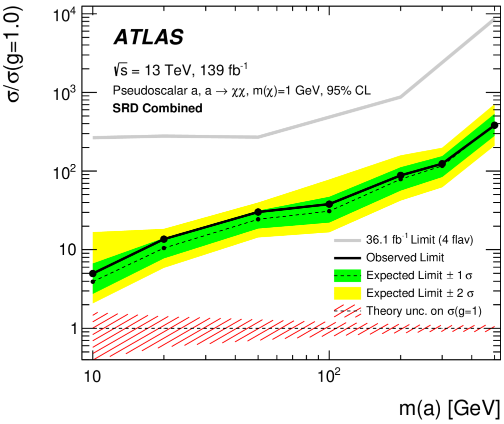

Figure 5 – Observed (solid) and expected (dashed) limits on the DM cross section obtained in the ATLAS SUSY search [14]. The x-axis refers to the mediator mass (m_{a}) and the y-axis is the cross-section divided by the theoretical prediction.

3 Conclusions

The LHC experiments have explored a very large phase space where DM could have existed. Recent theoretical developments encourage searches to look at more specific final states in addition to the inclusive ones, and several new results from both CMS and ATLAS have already expanded the horizons of DM searches. There are many ongoing full Run 2 DM searches that will further broaden the coverage. More dedicated triggers and reconstruction technologies are being developed to improve the search sensitivities.

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