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ATLAS Latest Dark Matter Searches

Nikolai Fomin,[a,*] **on behalf of the ATLAS Collaboration**[1]

[a] *University of Cambridge,*
United Kingdom

E-mail: fominik@gmail.com

The presence of a non-baryonic Dark Matter (DM) component in the Universe is inferred from the observation of its gravitational interaction. If DM interacts weakly with the Standard Model (SM) it could be produced at the Large Hadron Collider. The ATLAS experiment has developed a broad search program for DM candidates, including resonance searches for the mediator which would couple DM to the SM, searches with large missing transverse momentum produced in association with other particles called mono-X searches, and searches where the Higgs boson provides a portal to DM. The results of recent searches on $\sqrt{s}$ = 13 TeV pp data, their interplay and interpretation are presented.

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*Speaker

1. Introduction

A range of cosmological observations support the existence of Dark Matter (DM). Many theoretically viable models suggest that the DM could be particle-based. There are, however, no good DM candidates in the Standard Model (SM). This motivates DM searches at the Large Hadron Collider (LHC) [1], complementing the direct and indirect DM detection experiments. The DM searches are an important part of the physics programme of the ATLAS Collaboration [2], including both simplified- and full-models interpretations.

2. Simplified DM Models

The common choice of DM simplified models is vector/axial-vector (V/AV) s-channel exchange. These models are defined by only a few parameters – DM mass, mediator mass and its coupling to DM/SM. The complementary key signatures are missing transverse momentum (E_T^{miss}) with a SM particle X (usually jet/γ/Z/W), and dijet and dilepton resonances. Scalars or pseudo-scalars (S/PS) as mediators are other possibilities, often in association with heavy flavour quarks. Typical examples of such processes are shown in Figure 1.

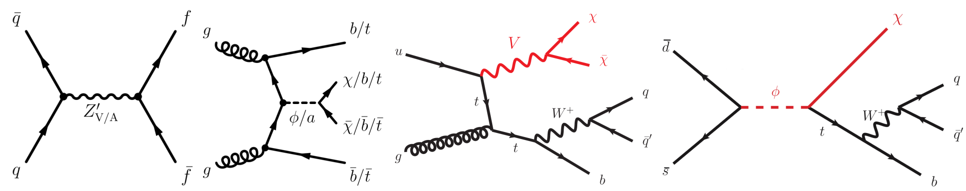

Figure 1: Representative Feynman diagrams of the simplified Dark Matter models. From left to right: V/AV mediator decaying into a fermion pair, S/PS mediator produced in association with a pair of third-generation quarks and decaying into DM, single top-quark production in association with a V, S mediator.

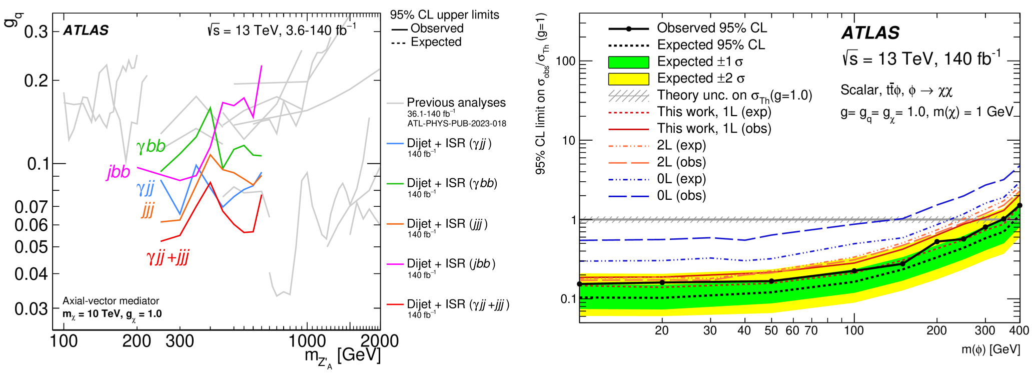

Figure 2: Limits set by the low mass dijet resonance [3] (left) and combination of $t\bar{t} + E_T^{\text{miss}}$ with 0/1/2 leptons [4] (right) searches.

Dijet resonance searches are limited by the trigger bandwidth for masses below 1 TeV. An ISR jet or photon recoiling against the mediator can be an additional particle to trigger on, giving access to lower resonance masses. The low mass dijet resonance search in Ref. [3] considers both jet and b-tagged jet pairs in combination with ISR jets and photons. The γjj and tri-jet channels are combined to boost the sensitivity in the mass range of 250 – 800 GeV, improving the limits up to 50%. The jbb channel is used to extend the sensitivity to the previously uncovered mass range of 200 – 250 GeV, see Figure 2.

An S/PS mediator can be produced in association with two top quarks. The search presented in Ref. [4] considers s-channel DM models, using custom resolved top-quark tagging to target final states with exactly one top-quark decaying leptonically. In addition to setting the limits on the mediator mass, the analysis performs a combination with searches considering fully leptonic and fully hadronic top decays. The DM mediators with masses up to 370 GeV are excluded, see Figure 2.

Models with scalar and vector mediators can produce signatures with a mono-top-quark and E_T^{miss} from mediators decaying into DM. The mono-top analysis in Ref. [5] targets these final states and uses a custom DNN-based top tagger allowing the selection of events with both zero and one b-jet in the final state. Novel signal reweighing techniques are utilized, resulting in a high-granularity four-dimensional parameter space in mediator and DM masses and coupling strengths. The exclusion limits are improved by 800 (300) GeV for scalar (vector) mediators.

3. 2HDM+a Models

The extended Higgs sector of the 2HDM models could interact with the DM via a pseudo-scalar mediator a. This gives rise to a class of models with rich phenomenology, called 2HDM+a. Mono-Higgs and mono-Z signatures provide strong sensitivity, along with the two/four top-quarks or $tbH^{\pm}(\rightarrow tb)$ channels.

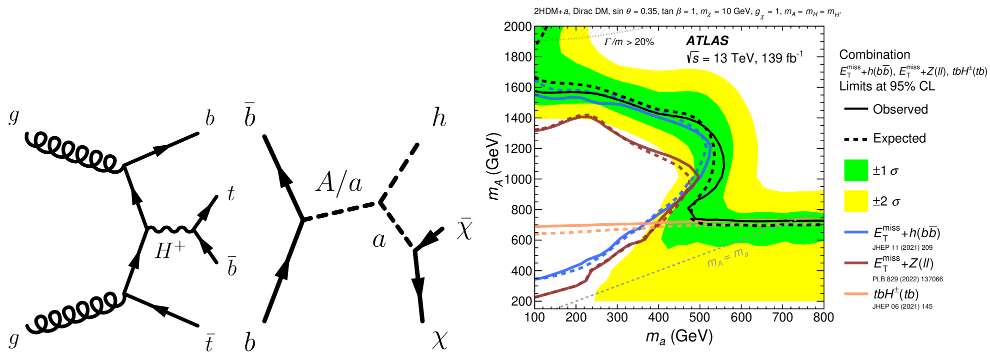

Figure 3: Feynman diagrams of the $tbH^{\pm}(\rightarrow tb)$ and mono-Higgs processes in the 2HDM+a model (left) and limits set by the combination of the three most sensitive searches (including $tbH^{\pm}(\rightarrow tb)$ and mono-Higgs analyses) to the 2HDM+a parameter space [6] (right).

The ATLAS Collaboration has performed a range of searches to cover the possible 2HDM+a signatures with the Run 2 dataset. A combination of the three most sensitive and complementary channels has been performed in Ref. [6], increasing the sensitivity to the previously uncovered parts of the parameter space, as demonstrated for one of the considered benchmarks in Figure 3. For this particular benchmark, the exclusion limits on the mediator mass a are improved by up to 50 GeV.

Type-II 2HDM/2HDM+a models predict heavy (pseudo-)scalars that can decay into top-quarks pairs. A dedicated search, which considers signatures with one or two leptons and b-tagged jets is presented in Ref. [7]. The analysis accounts for the strong interference with the SM top-quarks pair production, that would occur for such a process. This necessitates the use of specialized fit and limit-setting procedures taking the SM interference into account. The results are interpreted in the benchmark 2HDM+a DM models, excluding values of $\tan\beta$ below 0.9 across the probed range.

4. Dark Sector Models

The main assumption of dark (or hidden) sector models is existence of particles not interacting directly with the strong, weak, or EM sectors of the SM; they interact with the SM only via portals or mediators. Such models are phenomenologically attractive as they are only mildly constrained by the existing SM precision measurements, and can fill several gaps in the SM (e.g., lack of DM candidates and baryon asymmetry). Experimental signatures can also be quite diverse and unlike those typically considered in searches.

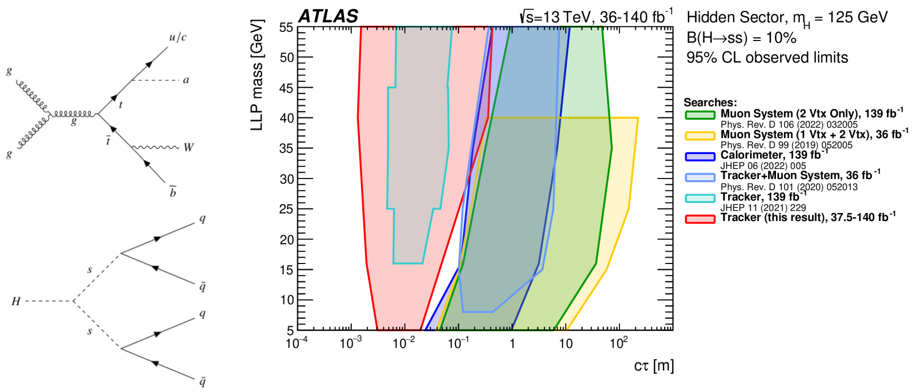

Figure 4: Representative Feynman diagrams of top quarks decaying into an ALP a (top left) and a Higgs boson decaying into a pair of neutral spin-0 dark sector bosons s (bottom left), and the limits set by the displaced vertices search [8] (right).

Higgs bosons decaying into pairs of dark sector particles and ALP models can give rise to long lived particles (LLPs). The signature considered is displaced jets and a leptonically decaying vector boson. Additionally VBF Higgs production is considered using dedicated VBF triggers. This is the first ATLAS search [8] to directly utilize improved track reconstruction in the Inner Detector suppressing false positives and improving the sensitivity. The search improves the existing limits on the hidden sector LLPs by a factor of 10 and bridges the coverage gap with calorimeter LLP searches, see Figure 4. First limits on photophobic $t \to aq$ ALPs production are set.

Dark sector models can have a Higgs-like mechanism with a new scalar s (dark Higgs). Light s would mix with the SM Higgs, resulting in a low mass $b\bar{b}$ resonance and E_T^{miss} in the final state. These type of models are interesting as they can accommodate the relic density constraints quite naturally. The search presented in Ref. [9] utilizes a mass-agnostic $X \to bb$ tagger, targeting both the merged and resolved topologies. The limits on the mediator mass are set for the low-mass s, excluding mediator masses up to 3.4 TeV and complementing the existing high-mass searches, as shown in Figure 5. The expected sensitivity is improved by up to 800 GeV compared to the previous result. For the first time, the limits are also set on cosmological relic-density-compatible models, where the floating DM coupling strength allows all considered model parameters to satisfy the relic density constraints.

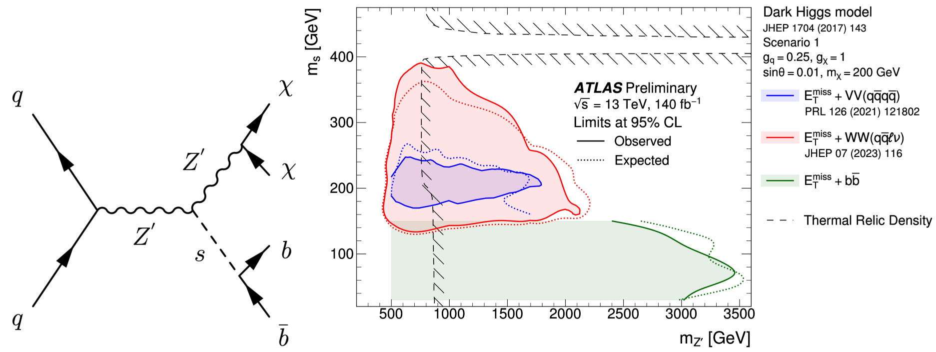

Figure 5: Feynman diagram of the decay of DM mediator Z' into a dark Higgs s and DM candidates (left), limits set by the low-mass dark Higgs decaying to a pair of b-quarks search [9] (right).

Strongly-coupled dark sector models predict pair-production of dark pions, further decaying into SM particles, with heavy flavour decay modes being the dominant ones. The search presented in Ref. [10] considers signatures with two or three top-quarks and two or one bottom-quarks. Due to the high jet multiplicity, ATLAS transverse energy (H_T) jet triggers can be used efficiently. Dark pions with mass up to 434 GeV and in the range of 280 – 522 GeV are excluded, depending on the model parameter choice.

5. SUSY-motivated Searches

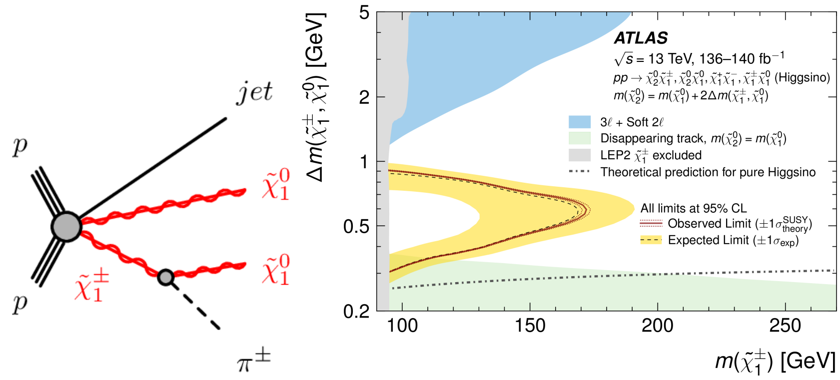

Figure 6: Feynman diagram for the almost mass-degenerate Higgsino production with an ISR jet (left) and the limits set by the search [11] (right).

Almost mass-degenerate higgsinos can provide viable DM candidates. Existing prompt and LLP higgsino searches leave a coverage gap at $\Delta m(\chi_1^{\pm}, \chi_0) = 0.3 - 1$ GeV. Signatures with soft, mildly displaced pions (or leptons) allow access to this regime, where "mildly" means that most charged particles are passing through the innermost tracking layers of the Inner Detector. The analysis presented in Ref. [11] considers ISR topologies to increase sensitivity to lower mass-splitting, and to reduce the background. An example Feynman diagram of the process and the limits set by the search are shown in Figure 6.

The ATLAS Collaboration also performs a large-scale reinterpretation programme of electroweak SUSY searches, in the electroweak pMSSM scans reported in Ref. [12]. In addition to a generic SUSY models scan, a scan is performed for bino-like neutralino DM candidates that satisfy relic density constraints. The results show that the ATLAS Run 2 SUSY searches have placed strong constraints on bino-like DM with LSP masses lower than 100 GeV, with only Z/h funnel production mode remaining viable in that regime, see Figure 7 .

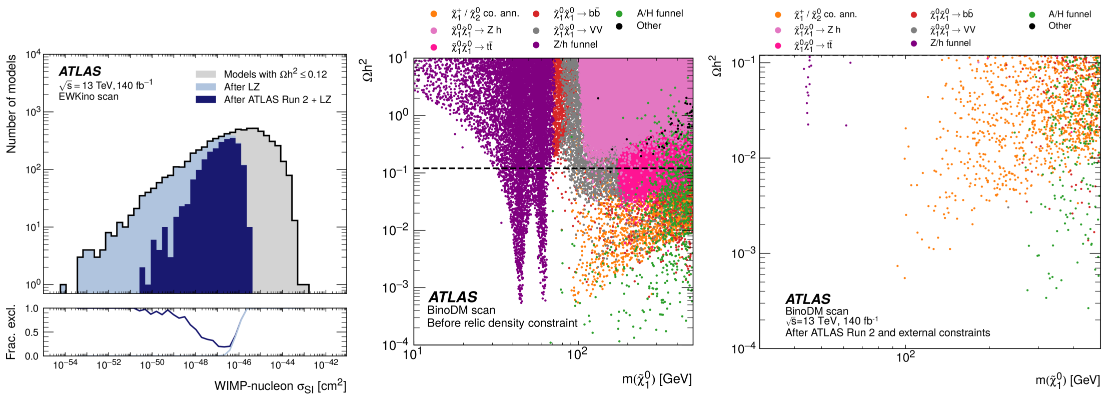

Figure 7: One-dimensional distribution of the WIMP–nucleon spin-independent scattering cross-section (left), and scatter plots of models selected from the BinoDM scan before the relic density constraint is applied (middle) and after both ATLAS Run 2 and external constraints are applied (right) [12].

6. Conclusion

The ATLAS Collaboration has an active DM search programme, exploring a wide range of signatures. Both simplified models and ultraviolet complete models are considered, with an increasing interest in the dark sector models as the source of DM. A selection of recent results utilizing the full LHC Run 2 dataset and improved reconstruction and analysis techniques has been highlighted.

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