PROCEEDINGS OF SCIENCE

Searches for dark matter with the ATLAS detector

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Despite several observational evidence for dark matter, there is no experimental hint on its nature so far. As a result, a plethora of scenarios extending the standard model of particle physics can accommodate dark matter-related observations while escaping the latest experimental constraints. In this context, one of the main approaches pursued by the ATLAS collaboration at the LHC is to search for weakly-interacting massive particles with minimal assumptions, which we give a brief overview in this document.

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1. Introduction: weakly-interating massive particles hunting with the ATLAS detector

Many dark matter (DM) models rely on the existence of hypothetical weakly-interacting massive particles (WIMP) [1]. WIMP with a mass in the 1 to 1000 GeV range in thermal equilibrium in the early Universe would freeze-out at the abundance reported by DM-related observations assuming weak interaction ($< \sigma v >\sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$) with standard model (SM) particles. This feature is quite generic, includes minimal assumptions and involves new physics at the TeV scale, making the WIMP model a flagship target for searches at the ATLAS experiment [2] at the LHC [3]. The searches for WIMP at the LHC typically rely on the reverse process with respect to the one which supposedly occurred during the thermal freeze-out, where two SM particles interact to create a pair of WIMP (DM, also labeled χ), with the addition of an extra radiation in the final state (labeled X), see Figure 1, leading to so-called 'mono-X' signatures. The presence of X in the final state is required to trigger the data-taking as the WIMP escape the collision undetected. Many different mono-X signatures have been explored by ATLAS, as discussed in the following sections.

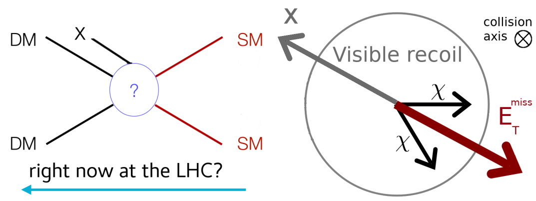

Figure 1: Schematics of (left) the typical WIMP pair production mode at the LHC and (right) the topology of a WIMP pair production event in the plane transverse to the collision.

The ATLAS detector recorded 139 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV during the run 2 of data-taking (2015-2019). This very large dataset includes millions of Higgs bosons, hundreds of millions of top quarks and thousands of millions of Z bosons. The ATLAS detector is a multi-purpose apparatus with a high efficiency and acceptance throughout a wide range of energies and angles which allows for advanced particle identification. Its excellent online and offline reconstruction performance are illustrated in Figure 2 left and right, respectively, for kinematics quantities relevant to mono-X searches, namely the missing transverse energy ($\mathrm{E}_\mathrm{T}^\mathrm{miss}$) [4], which would correspond to the sum of the transverse momenta (p_T) of the WIMP in a signal event, and the jet energy scale (JES) [5], which is a key quantity to reconstruct $\mathrm{E}_\mathrm{T}^\mathrm{miss}$ precisely.

2. Mono-jet search analysis

In the mono-jet analysis [6], mono-X events in which the X system is composed by at most 4 jets well separated from the $\mathrm{E}_\mathrm{T}^\mathrm{miss}$ are selected, the leading jet p_T being greater or equal than 150 GeV. The main background originates from $Z(\rightarrow \nu\nu)$+jets events and $W(\rightarrow \ell\nu)$ + jets events in which the charged lepton is misidentified or out of acceptance. These are estimated with Monte Carlo simulations corrected by state-of-the-art predictions [7] to which the normalisation is constrained in data control regions including one and two charged leptons. The total uncertainty in the background prediction reaches 2-4%, with a significant contribution originating from the

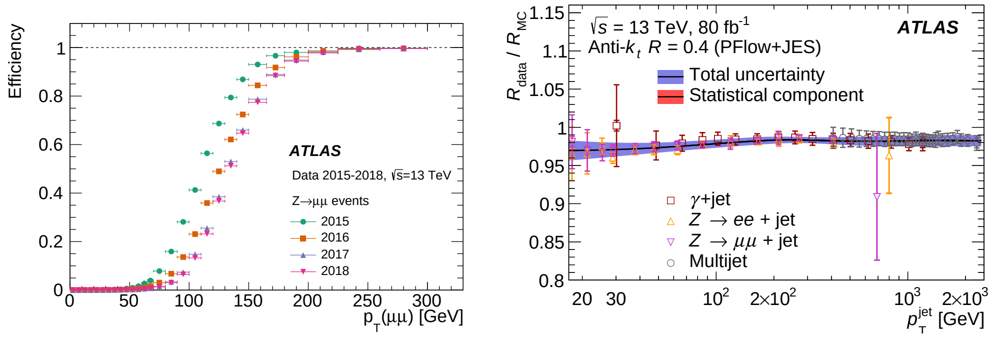

Figure 2: Measurement of (left) the lowest unprescaled missing transverse energy trigger efficiency [4] and (right) the jet energy scale [5] in ATLAS during the run 2 of data-taking (2015-2018).

uncertainty in the QCD and EW corrections of the predictions. No excess over the background predictions are observed, see Figure 3. The results are used to set competitive exclusion limits on several WIMP models. One of them considers DM interactions mediated by an axial vector, Z_A, and can be compared under some model assumptions to the limits set by DM direct detection experiments, see Figure 4 (top row). In this model, the mediator couples to SM particles such that direct searches for SM-decaying mediators with narrow width are performed by looking for a bump over smoothly falling background, e.g. in the di-jet mass spectrum. The complementarity of both approaches is illustrated in Figure 4 (bottom row) for various coupling assumptions [8].

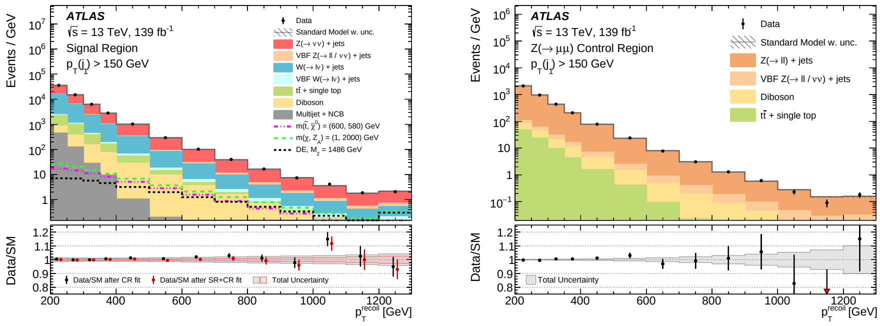

Figure 3: Comparison between the data and the background model in (left) the signal-enriched region and (right) the Z + jets background control region [6].

3. Searches with third generation quarks

Models with spin-0 mediators under the minimal flavour violation hypothesis are better probed by studying collision events including third generation quarks in the final state, as the coupling between the mediator and the SM particles is Yukawa-like and therefore scales with the particle masses. Representative diagrams are shown in Figure 5, top left. The ATLAS research program covers the $b\bar{b}$+E_T^{miss} [9] and the $t\bar{t}$+E_T^{miss} final states, including final states with 0 to 2 leptons [10]. Complementary sensitivity at high mediator mass is obtained with $b\bar{b}$ and $t\bar{t}$ resonance searches, in a similar way than di-jet resonances for the vector scenario described in the previous section. The program has been recently extended to tq/tW+E_T^{miss} final states (topic of a dedicated talk at this

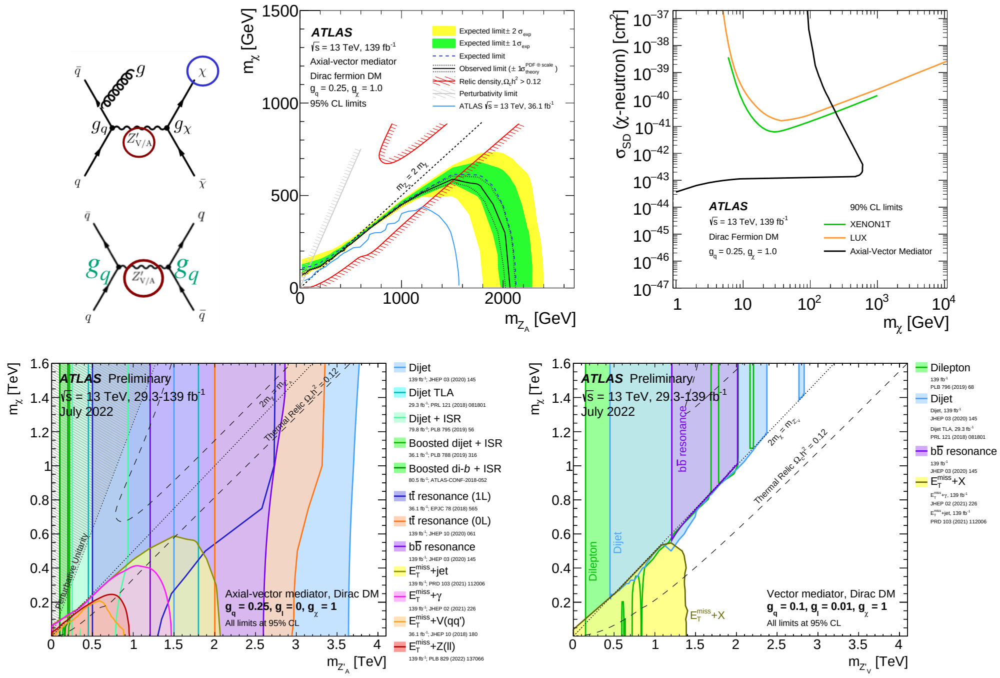

Figure 4: Exclusion limits for a model considering DM interactions mediated by an axial vector particle Z_A (top) [6] set by the mono-jet analysis and (bottom) set by mono-X and resonance searches under various coupling assumptions [8]. Representative production diagrams are shown in the top-left corner.

conference) as well as to $t\bar{t}$+$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ final states with lower $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$, including a statistical combination of all $t\bar{t}$+$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ channels (0-lepton low $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$, 0-lepton, 1-lepton and 2-lepton) [10]. The $t\bar{t}$+$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ search at lower $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ uses a combination of $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ and b-jet triggers to access the lower $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ region. It deals with the large background originating from semi-leptonic top decays with a missed lepton by defining several regions allowing to constrain separately the normalisation of tW+jets, $t\bar{t}$+jets and $t\bar{t} + b$ events. Data is found to be compatible with the SM background predictions within 2σ and the results are interpreted in terms of exclusion limit as shown in Figure 5, top right and bottom. The 2-lepton channel dominates the sensitivity throughout the mediator mass range considered and the 0-lepton extension at low $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ alone reaches the expected sensitivity of the 1-lepton channel at low mediator masses. For a scalar mediator, masses below 370 GeV are excluded for unity coupling, whereas couplings above 0.17 are excluded for a mediator mass fixed to 10 GeV. Results for a pseudo-scalar mediator particle are also available as well as comparisons to the limits from direct detection experiments.

4. Searches for Higgs to invisible decays

The Higgs boson could also be mediating DM interactions, a scenario which can be seen as a particular case of spin-0 mediator[1]. In this context, invisible decays of the Higgs are searched for

[1]in that scenario however, the mediator (which is the Higgs boson) also couples to vector bosons whereas this coupling is set to zero in the spin-0 model. This can lead to large phenomenological differences, e.g for single-top-associated production where the cross section is much larger in the spin-0 model than in the Higgs to invisible scenario.

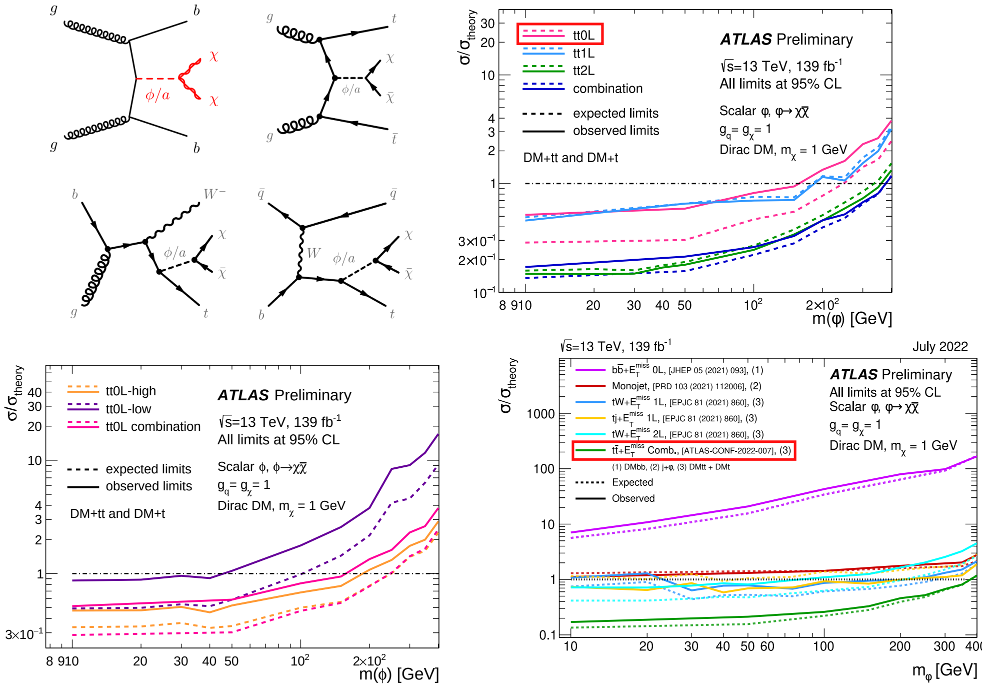

Figure 5: Exclusion limits for a model considering DM interactions mediated by a scalar particle, ϕ, by (top, right) the various $t\bar{t}$+E_T^{miss} channels [10], (bottom, left) the two $t\bar{t}$+E_T^{miss} 0-lepton channels [10] and (bottom, right) all the relevant channels published by ATLAS [8]. Some representative diagrams are shown in the top-left corner.

assuming SM production modes. The most sensitive channels in ATLAS are VBF production (VBF + E_T^{miss}) [11], Z-associated production ($Z \to \ell\ell$ + E_T^{miss}) [12] and top-pair-associated production ($t\bar{t}$+E_T^{miss}) [10], leading respectively to an expected (observed) limit on the branching ratio of Higgs to invisible to 0.103 (0.145), 0.19 (0.19) and 0.30 (0.40), in the absence of significant excess above background predictions. The VBF and ZH channels are typically more sensitive than $t\bar{t}H$ but also more systematically-dominated and rely on the HVV coupling to be SM-like whereas the $t\bar{t}H$ channel is independent from it. Partial run 1 + run 2 combined results are available in [13] and the full combination of run 1 + run 2 results is in progress.

5. Conclusion & outlook

As a summary, the ATLAS collaboration is very actively searching for WIMP based on simplified single mediator models, leading to mono-X signatures, but also to Higgs portal models, which lead to the Higgs to invisible searches. A number of more UV complete models not discussed here are also being investigated in parallel by the ATLAS collaborations, such as the 2 Higgs doublet + pseudo-scalar model (2HDM+a) [14] and the dark Higgs model [15], for which summary plots are shown in Figure 6. These models involve more parameters but also give rise to extra experimental signatures such as mono-H (2HDM+a) or VV+E_T^{miss} (dark Higgs).

Such a very large variety of signatures can be explored thanks to the excellent performance of the ATLAS detector at the LHC, which provide a sensitivity typically more model-dependent but

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offering a nice complementarity with other experiments such as DM direct detection experiments. Other ATLAS talks at this conference give additional details on specific analyses.

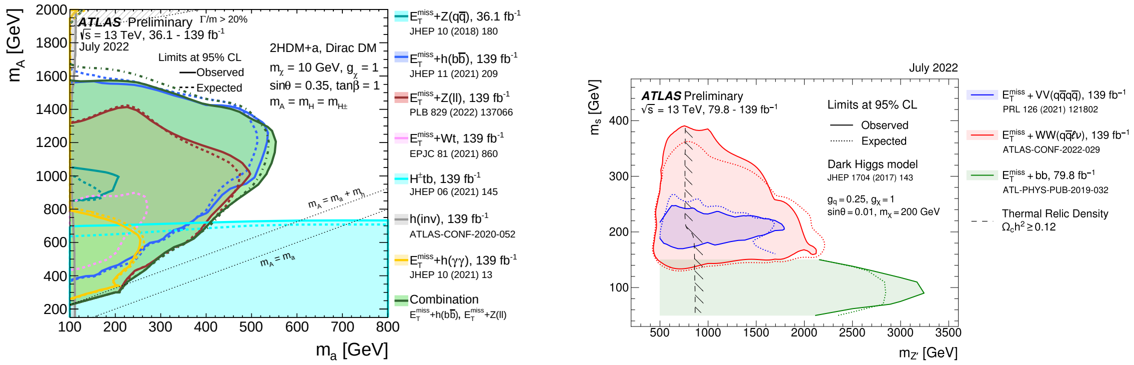

Figure 6: Summary plots of the existing limits set by the ATLAS experiment (left) on the 2HDM+a model and (right) on the dark Higgs model [8].

References

[1] G. Steigman and M. S. Turner, Nucl. Phys. B **253** (1985), 375-386

[2] ATLAS Collaboration, JINST **3** (2008), S08003

[3] L. Evans and P. Bryant, JINST **3** (2008), S08001

[4] ATLAS Collaboration, JHEP **08** (2020), 080

[5] ATLAS Collaboration, Eur. Phys. J. C **81** (2021) no.8, 689

[6] ATLAS Collaboration, Phys. Rev. D **103** (2021) no.11, 112006

[7] J. M. Lindert *et al.* Eur. Phys. J. C **77** (2017) no.12, 829

[8] ATLAS Collaboration, ATL-PHYS-PUB-2022-036, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-036/

[9] ATLAS Collaboration, JHEP **05** (2021), 093

[10] ATLAS Collaboration, ATLAS-CONF-2022-007, https://cds.cern.ch/record/2805211

[11] ATLAS Collaboration, JHEP **08** (2022), 104

[12] ATLAS Collaboration, Phys. Lett. B **829** (2022), 137066

[13] ATLAS Collaboration, ATLAS-CONF-2020-052, https://cds.cern.ch/record/2743055

[14] LHC Dark Matter Working Group, Phys. Dark Univ. **27** (2020), 100351

[15] M. Duerr *et al.*, JHEP **04** (2017), 143