Dark Matter searches with the ATLAS Detector

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Abstract

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 experiment has developed a broad search program for DM candidates, including resonance searches for the mediator which would couple DM to the SM. The results of recent searches on 13 TeV pp data, their interplay and interpretation will be presented. Prospects for HL-LHC will also be discussed.

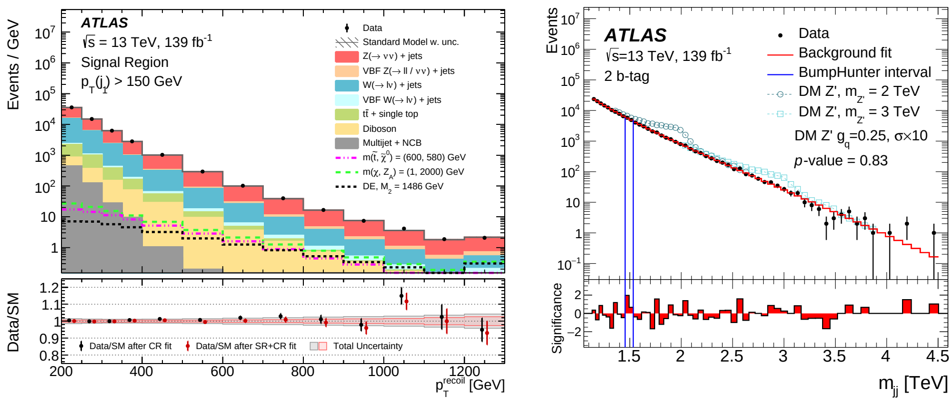
1 Introduction

For LHC Run-2, a set of simplified DM benchmark models have been defined by the LHC DM working group. These are described in Ref. [1], and have been proposed to investigate the particle nature of DM at the LHC. The free parameters of such models are: the mediator's nature (either (pseudo-)scalar or (axial-)vector), its mass ($m_{Z'}$), the mass of DM particles (m_χ), and the coupling between the mediator respectively to SM quarks (g_q) and to DM (g_χ) particles. No interactions with other SM particles are hypothesised. These models are tested with the ATLAS detector [2] in final states including jets and large missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). Recent results are discussed in this document.

2 Search for dark matter in events with jets

The monojet search [3], performed with $139\,\mathrm{fb}^{-1}$ of pp collisions collected by the ATLAS experiment during the Run-2 of the LHC, exploits the shape of the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution to enhance the sensitivity to new physics phenomena. Events are selected with an $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and by requiring at least one jet with transverse momentum (p_{T}) greater than $150\,\mathrm{GeV}$. Targeted signal models do not foresee either leptons or photons in the final states, thus events containing such reconstructed objects are vetoed. Backgrounds processes are dominated by the associated production of a W or a Z boson (referred to as V in the following) with jets, while minor contribution arise from top quark and dibosons processes. The QCD background sharply increases at low $E_{\mathrm{T}}^{\mathrm{miss}}$ due to mis-measurements of jets in the final states, which lead to fake $E_{\mathrm{T}}^{\mathrm{miss}}$. Orthogonal control regions (CR) enriched in Z($\rightarrow \ell\ell$)+jets and W($\rightarrow \ell\nu$)+jets processes are defined. In these, leptons are treated as invisible particles and the $E_{\mathrm{T}}^{\mathrm{miss}}$ is replaced by the total momentum recoiling against jet activity, $\mathrm{p}_{\mathrm{T}}^{\mathrm{recoil}}$. The CR are used to correct the Monte Carlo (MC) predictions of the backgrounds, and help to constrain modelling and detector systematic uncertainties. Higher order QCD and electroweak (EW) corrections are applied to V+jets processes simulations adopting theory calculations provided by Ref. [4]. EW effects are sizeable in the TeV range, with negative corrections to the $p_{\mathrm{T}}(\mathrm{V})$ distributions up to 20 to 30%. Systematic uncertainties provided by the authors take into account missing higher orders and unknown mixed QCD+EW corrections. These calculations allow to correlate the estimate of W and Z+jets processes in the likelihood fit, leading to a reduction of the uncertainties on the dominant background process, $Z(\to \nu\nu)$+jets.

In Fig. 1a the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the signal region is compared with SM predictions. A background only fit is performed to the control regions (CR) or to the control and signal regions simultaneously (SR+CR). All events with $E_{\mathrm{T}}^{\mathrm{miss}} > 1.2\,\mathrm{TeV}$ are included in the last bin. The total uncertainty on the background predictions ranges between 1.2 and 4%. The dominant uncertainties are due to the modelling of V+jets processes and the measurement of high energetic hadronic jets. Uncertainties on the measurement of leptons are also relevant, since CR enriched in leptonic final states are present in the fit model.



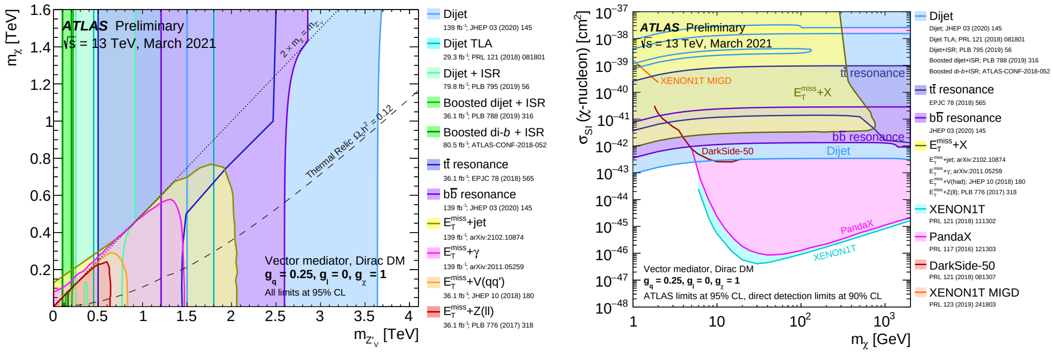
(a) (b)

Figure 1: (a) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution compared with SM predictions (see text). Benchmark signals distributions are represented with dashed lines. Figure from [3]. (b) Invariant mass distribution of two jets (see text). Figure from [5].

The resonant production of a Z' mediator is looked for in the invariant mass distribution of two jets [5]. The challenge is to model the SM QCD backgrounds without introducing any bias that would hide a signal. Due to limitations in the single-jet trigger thresholds, this search is limited to $m_{\mathrm{jj}} > 1\,\mathrm{TeV}$. To enhance the sensitivity to particular DM models and suppress SM backgrounds, SR requiring the presence of exactly one or two b-tagged jets are also defined. A fit to the m_{jj} distribution is performed to estimate the QCD background with a smoothly falling function. This is validated either with pseudodata derived from previous results [6], or by inverting the requirements which define the SR for b-tagged spectra. The backgrounds is estimated using the sliding-window fitting technique, described in Ref. [6]. Uncertainties on the background estimate from the choice of the fit function reach up to 10% in the tail of the m_{jj} distribution. From the statistical fluctuations of the fit parameters obtained in various pseudo-experiments an uncertainty up to 30 to 40% in the tail is derived. Spurious signal tests are performed to check the stability of the sliding-window-fitting technique, and no bias in the background estimate is introduced by the Z' models considered.

The BumpHunter algorithm [7] performs a scan of the m_{jj} distribution in variable size intervals and evaluate the significance of the deviations between data and the background estimate. A global p-value is then determined for each bin using pseudo-experiments. Figure 1b shows the invariant mass distribution of two jets applying the 2 b-tag selection described in Ref. [5]. The interval which shows the largest discrepancy between data and the background estimate is highlighted with the blue lines. Benchmark Z' signals are shown on top of the background distribution. The results of the bump-hunting procedure in each bin is reported in the lower pad, and no significant deviation from the backgrounds predictions is observed.

Limits on the parameters of simplified DM models are set by the two searches described above. Results are shown for a vector mediator in Figure 2a in the $(m_{Z'}, m_\chi)$ plane. Results are shown for fixed values of the couplings g_q, g_χ, but also other hypotheses, as reported in Ref. [8], are tested. While the monojet search is sensitive only in the on-shell regime, resonant searches target only the mediator production, thus are almost independent from m_χ.

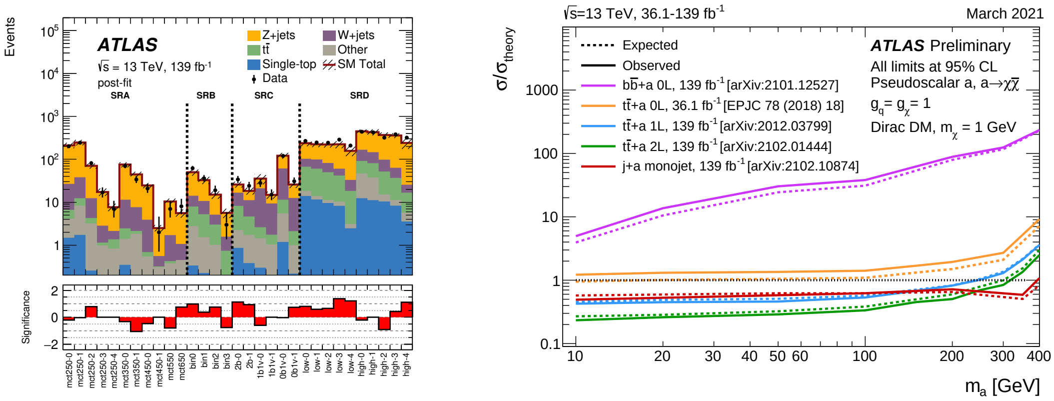


(a) (b)

Figure 2: (a) Results on benchmark simplified DM model including a vector mediator and fermionic WIMPs. (b) Comparison of ATLAS results to direct-detection DM experiments in the case of a spin-independent interaction between WIMPs and nucleons. Figures from [8].

These results are converted to limits on the spin-independent interaction cross-section between nucleons and WIMPs, and compared to the ones obtained by direct-detection (DD) DM experiments. As shown in Figure 2b, ATLAS provides sensitivity to lower WIMPs mass values. With more data which will be collected during Run-3 and the high-luminosity phase of the LHC, smaller interaction cross-sections will be probed. ATLAS results though depend on the choice of the couplings g_q and g_χ, and might change significantly for other choices.

Simplified dark matter models which consider a scalar/pseudo-scalar mediator, hypothesise a Yukawa-like interaction with the SM particles. Thus the sensitivity to such signals is enhanced by targeting final states which involve heavy flavour (HF) jets. The search for new phenomena in $b\bar{b} + E_{\mathrm{T}}^{\mathrm{miss}}$ final states [9] targets such benchmark signals. Events are selected by applying a $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger. Two b-jets are required applying a multivariate discriminant which provides an average 77% tagging efficiency. To keep event selection criteria as low as possible, a cut on the product of the leading jet and the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event is applied. Residual SM backgrounds are V+HF jets and $t\bar{t}$ production. A set of multivariate discriminants is adopted to provide additional separation power between signal and backgrounds. These exploit the topology of the events, such as the angular distance between the b-tagged jets and the direction of missing transverse momentum, and the quality of the reconstruction of the $E_{\mathrm{T}}^{\mathrm{miss}}$. The final discriminant variable adopted in this search is the binned distribution of $cos\theta^*_{bb}$, as defined in [9]. Dedicated Z+$\geq$ 2 b-jets CR are introduced to correct SM MC predictions. The main limitation of this search is the modelling of the Z+HF processes, which has an associated yield uncertainty between 10 to 20% in the considered regions. Figure 3a shows a summary of the signal regions defined in the search. The DM dedicated regions are indicated by SRD (signal region D). No significant deviations from the background predictions are observed, thus limits at 95% confidence level (CL) on simplified DM models are set.



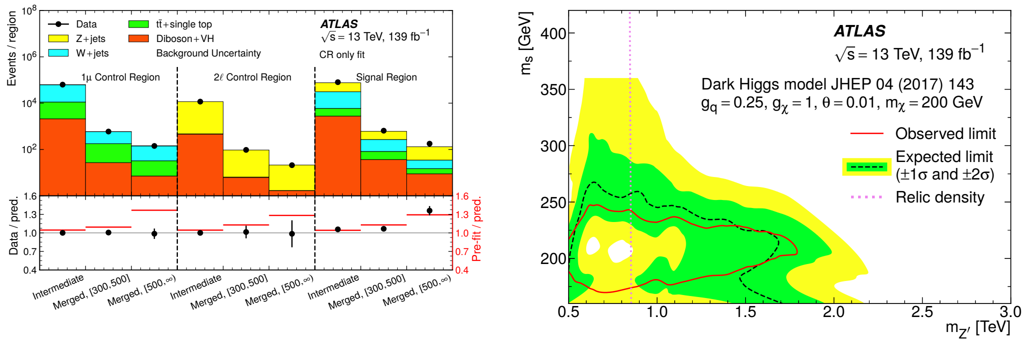
(a) (b)

Figure 3: (a) Summary plot of the regions defined in the search for DM in $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ final states [10]. (b) Upper limits on the pseudo-scalar mediator mass, for fixed value of DM particles mass and couplings. Figure (b) from [8].

Complementary sensitivity to such models, which foresee a Yukawa-like coupling to SM particles, is achieved by the search for DM in $t\bar{t}$ $+E_{\mathrm{T}}^{\mathrm{miss}}$ final states [10]. This search targets events with 2 leptons and at least one b-tagged jet. Cuts are applied on the $E_{\mathrm{T}}^{\mathrm{miss}}$ significance and on the m_{T2} distributions, as defined in Ref. [10], which provide rejection of the $t\bar{t}$ dominant background. Signal regions are defined splitting the events according to the flavour of the leptons to improve sensitivity to the signals. Residual backgrounds are due to $t\bar{t}$ and $t\bar{t}$+Z production. Orthogonal CR are defined also in this case to correct the normalisation of such processes. The dominant uncertainties on the background predictions are due to jet measurements, $t\bar{t}$ processes modelling and to limited MC statistics. A good agreement between data and background estimate is observed. Upper limits set on the mass of a pseudo-scalar mediator, for 1 GeV WIMPs, are reported in Figure 3b. Results are obtained for fixed values of the couplings $g_q = g_\chi = 1$. Limits in the hypothesis of a scalar mediator are reported in Ref. [8].

Giving a mass to WIMPs: a search for the dark Higgs

A search for the production of a dark Higgs boson, s, has been performed by the ATLAS collaboration [11]. Fully hadronic final states are targeted to maximise the sensitivity to the $s \to VV$ signal [12]. This is the dominant decay mode for $m_s > 160$ GeV. Events with a large radius (R) jet and large $E_{\mathrm{T}}^{\mathrm{miss}}$> 200 GeV arising from the production of additional DM particles are targeted. To improve the measurement of the large R jet, and to catch the multi-prong structure of the s particle decay, the Track-Assisted Reclustered (TAR) jet algorithm is used [13]. This clusters R = 0.4 anti-kt jets into an anti-kt large-R jet (with R = 0.8), the TAR jet. Constituents are then matched to inner detector tracks, whose transverse momentum is rescaled to the one of the matched small-R jets, such that the energy deposits from neutral particles are taken into account. Corrected tracks are used to evaluate N-subjettines variables [14]. These provide discrimination between the 4-prong topology expected from the pair production of vector bosons and other SM processes. Two merged categories are defined based on the p_{T} of the TAR jet. Events failing the selection criteria based on the mass and the p_{T} of the TAR jet are included in an *Intermediate* category, if additional small R jets close to the TAR jet are found. Events with reconstructed leptons are included in orthogonal CR. These are single binned, follow the SR categorisation, and are used to correct the normalisation of the V+jets processes from MC simulations. The distribution of the invariant mass of the two vector bosons from which the dark Higgs candidate is reconstructed, is the discriminant variable in the SR.



(a) (b)

Figure 4: (a) Summary plot of the control and signal regions of the search for a dark Higgs in events with a large-R jet and $E_{\mathrm{T}}^{\mathrm{miss}}$. (b) Constraints on the parameters of proposed extended simplified DM models. Figures from [11].

Figure 4a shows the data-SM agreement in the control and signal regions of the analysis after a CR only fit in the background only hypothesis is performed. The dominant uncertainties on the SR backgrounds predictions are related to the modelling of V+jets processes and to the measurement of hadronic jets. A statistical fluctuation in the low-statistics highest-p_{T} merged SR is observed, but the excess is not significant. Limits are set on the parameters of the benchmark signal model considered at 95% of CL, and are reported in the ($m_{Z'}$,m_s) plane for fixed values of the couplings between the SM particles and the DM mediator, as shown in Fig. 4b.

3 Conclusion

No significant deviations from the SM backgrounds predictions have been observed in recent dark matter searches carried out by the ATLAS collaboration. Benchmark simple DM Z' mediators, with an axial vector nature and which couple to quarks, have been excluded up to masses of 3.6 TeV by resonant searches. The monojet search instead is able to exclude WIMPs of up to 650 GeV for $m_{Z'} \sim 1.8$ TeV. Pseudo-scalar mediators with a Yukawa-like interaction with SM quarks have been excluded up to around 400 GeV by both the monojet and HF jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ searches. Benchmark dark Higgs signals have been investigated with innovative jet reconstruction techniques, and masses between 100 and 240 GeV have been excluded for Z' masses in the range [0.5, 1.7] TeV for fixed values of other benchmark parameters.

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