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Search for dark matter with the ATLAS detector at the LHC

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Abstract. An overview of recent searches for dark matter production in association with visible particles with the ATLAS detector at LHC is presented. Interpretations of the results of the searches in terms of the effective field theory and simplified models is discussed. The exclusion limits placed by the ATLAS searches are compared to the constraints from direct dark matter detection experiments.

1. Introduction

Numerous astrophysical measurements provide compelling evidence for the existence of non-baryonic dark matter (DM) [1, 2]. However, non-gravitational interactions of the dark matter have not been observed, and little is known of its particle nature. The most studied dark matter candidate is a neutral weakly interacting massive particle χ (WIMP [3]), which can be pair-produced in pp collisions at high energy. The ATLAS experiment [4] has a rich program of searches for DM particles. The produced $\chi\chi$ pair would be invisible to the ATLAS detector, but the signatures with an additional visible final-state object X recoiling against large amount of missing energy can be detected. Therefore, the minimal distinctive signature of DM production is the mono-X final state, where X can be e.g. a jet, a gauge boson or a Higgs boson. A variety of such signatures has been examined at ATLAS [5–16]. Besides of the mono-X signatures the ATLAS searches also cover DM production in association with a pair of visible objects and dijet resonances produced by the decay of the particle mediating the interactions between the DM and the SM particles.

Most of the ATLAS searches for DM production in Run I of the LHC are performed in a model-independent way, in the framework of an effective field theory (EFT) [3, 17] which is parametrized only in terms of the mass of the DM particle m_χ and the suppression mass scale M_*. In the EFT the interaction of the DM particle with the Standard Model sector is described by contact operators, generated by integrating out heavy mediators. The applicability of the EFT approach is limited by requirement of the momentum transfer involved in the process to be small relative to the energy scale associated to the heavy mediator, $Q_{\mathrm{tr}} << M_*$. However, at the LHC the momentum transfer can reach large values at which the EFT is not valid.

The searches in Run II overwhelmingly utilize simplified models [18–21], where a single particle mediating the interaction between the DM particle and the SM sector is explicitly introduced. In this case, the free parameters are the DM mass m_χ, the mediator mass M_{med}, the width of the mediator Γ_{med}, the coupling of the mediator to quarks g_q, and the coupling of the mediator to the DM particle g_χ. A minimal mediator width is assumed in most of the searches. In the limit of large mediator mass, the simplified model description coincides with the EFT with the effective suppression scale $M_* = M_{\rm med}/\sqrt{g_q g_\chi}$.

2. Mono-jet search

The search for DM production in proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC using mono-jet final states is reported in [5]. The data correspond to an integrated luminosity of 3.2 fb^{-1} collected by the ATLAS experiment in 2015. The analysis selects events with an energetic jet and large missing transverse energy $E_{\rm T}^{\rm miss}$ in the final state, which is referred as the mono-jet signature. Several inclusive and exclusive signal regions (SRs) with increasing requirements on the missing transverse energy $E_{\rm T}^{\rm miss}$ between 250 and 700 GeV are optimized. The expected background is dominated by $Z(\rightarrow \nu\nu)$+jets and W+jets production processes. The contributions of the background processes to the SRs are estimated using dedicated control regions. The numbers of observed events in data are found to be in agreement with the SM predictions. The level of agreement is translated into exclusion limits on the masses of the DM and mediator particles under the assumption of a simplified model with an axial-vector mediator in the s-channel, Dirac DM particles, and couplings $g_q = 1/4$ and $g_\chi = 1$. Figure 1 shows the observed and expected 95% CL exclusion limits in the $m_\chi - m_A$ parameter plane. Mediator masses below 1 TeV are excluded at 95% CL for DM masses below 250 GeV. The results are translated into 90% CL exclusion limits on the spin-dependent χ-proton elastic scattering cross section as a function of the DM mass, as shown in figure 2, and compared to the constraints from the direct DM detection experiments XENON100 [22], LUX [23] and PICO [24, 25]. The search excludes χ-proton scattering cross sections above 10^{-42} cm^2 at 90% CL for DM masses below 10 GeV.

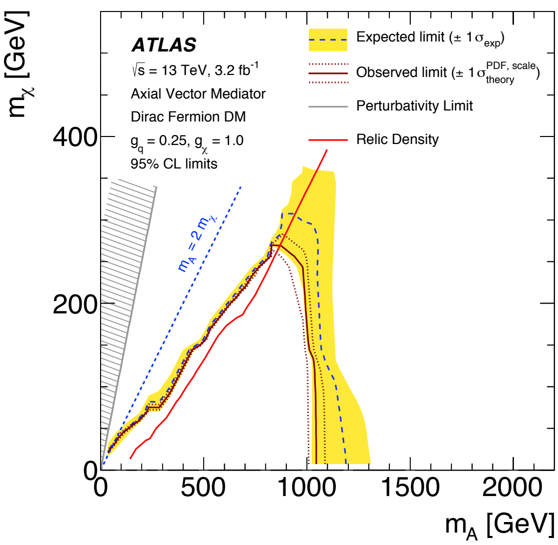

Figure 1. The observed and expected 95% CL exclusion limits in the $m_\chi - m_A$ parameter plane for a simplified model with an axial-vector mediator, Dirac DM particles, and couplings $g_q = 1/4$ and $g_\chi = 1$ [5].

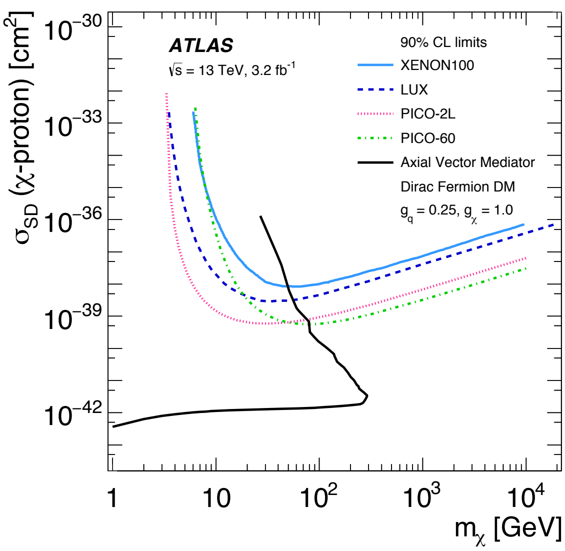

Figure 2. The inferred 90% CL exclusion limits on the spin-dependent χ-proton scattering cross section as a function of m_χ, compared to the constraints from direct DM detection experiments [5].

3. Mono-photon search

The mono-photon analysis [6], performed using data corresponding to an integrated luminosity of 3.2 fb^{-1} at $\sqrt{s}$ = 13 TeV, targets events with a single energetic photon, large $E_{\mathrm{T}}^{\mathrm{miss}}$, not more than one jet and no leptons in the final state. The SM predictions are in agreement with the measurements. The dominant background is the $\gamma+Z(\rightarrow \nu\nu)$ process, where the photon comes from initial state radiation (ISR). The results of the search for the mono-photon+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature are interpreted both in terms of the EFT and a simplified model with an axial-vector mediator. In the first case lower limits are placed on the effective mass scale M_* as a function of the DM mass and shown in figure 3. The search excludes values of M_* up to 570 GeV. Figure 4 shows the observed and expected 95% CL exclusion contours in the simplified model as a function of the DM mass and the mediator mass. Mediator masses below 710 GeV are excluded for DM masses below 150 GeV. The contour corresponding to the 90% CL exclusion limits on the χ-proton scattering cross section, is shown in figure 5 as a function of the DM mass m_χ, and is compared to the results from direct DM searches [22, 23, 27]. Stringent limits, at the order of 10^{-41} cm^2, are set on the scattering cross section up to DM masses of about 150 GeV.

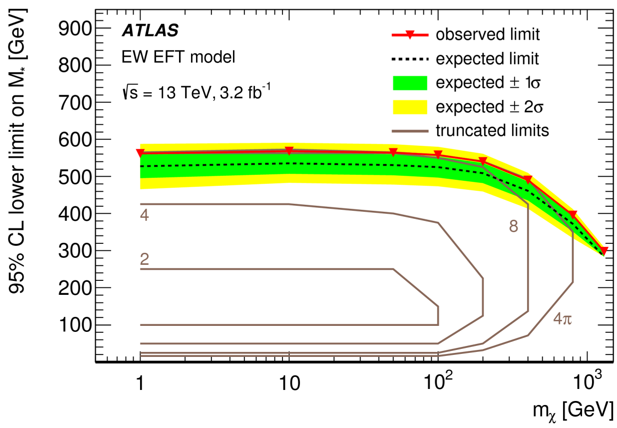

Figure 3. The observed and expected 95% CL limits on M_* for a dimension-7 operator EFT model as a function of DM mass [6]. When the EFT description becomes invalid, a truncation procedure is applied [26]. The effect of the truncation for the representative values of g^* (2, 4, 8 and 4π) is shown.

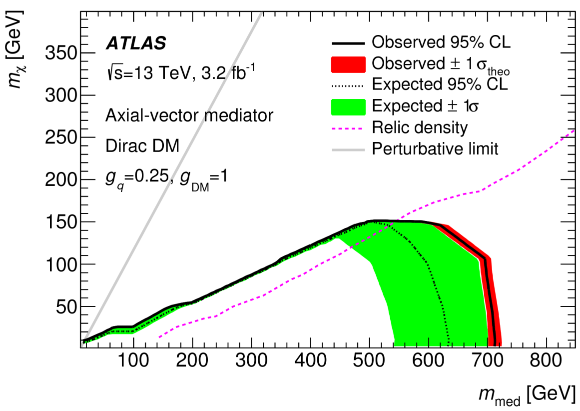

Figure 4. The observed and expected 95% CL exclusion limits for a simplified model of DM production with an axial-vector mediator, Dirac DM particles and couplings $g_q = 0.25$ and $g_\chi = 1$ as a function of the DM mass and the mediator mass [6].

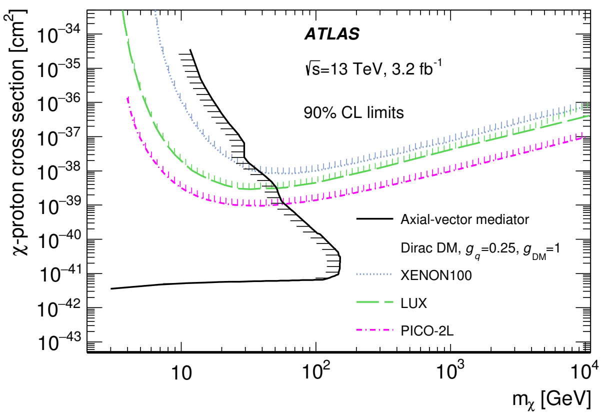

Figure 5. The inferred 90% CL exclusion limits on the χ-proton scattering cross section as a function of the DM mass m_χ in a simplified model of DM production involving an axial-vector operator, Dirac DM particles and couplings $g_q = 0.25$ and $g_\chi = 1$. Comparison with the result from direct DM detection experiments is also shown [6].

4. Mono-V search

The topology of the mono-$V + E_{\mathrm{T}}^{\mathrm{miss}}$ searches [7, 8] is a boosted boson recoiling against pair-produced DM particles. The first search [7] targets dark matter production in association with a hadronically decaying W or Z boson, using 3.2 fb^{-}1 of pp collisions at $\sqrt{s} = 13$ TeV. To reconstruct the W/Z boson in the boosted regime, the hadronic products of the produced quarks are captured by a high-p_{T} large-R jet. No statistically significant excess over the Standard Model prediction is observed. The dominant source of background events is $Z(\to \nu\nu)$ production in association with jets. Two theoretical models are used as benchmarks: the EFT and a vector-mediated simplified model. Exclusion limits are placed on the mass scale M_* in the EFT model and on the signal strength for a vector-mediated simplified model generated with couplings $g_q = 0.25$ and $g\chi = 1$.

5. Mono-Higgs search

The signature targeted by the analysis reported in [13] is large $E_{\mathrm{T}}^{\mathrm{miss}}$ and a Higgs boson decaying to a pair of bottom quarks. The analysis uses 3.2 fb^{1} of pp collisions at $\sqrt{s} = 13$ TeV. The $b\bar{b}$ system is reconstructed with either a pair of small-R jets, or a single large-R jet with substructure in the boosted regime. The search is performed by implementing a shape fit of the reconstructed dijet mass m_{jj} or single large-R jet mass distribution. The background is dominantly composed of SM W/Z+jets and $\bar{t}t$ events. Results are interpreted using a simplified model with a Z' gauge boson mediator and a two-Higgs-doublet model containing an additional Z' boson which decays to a SM Higgs boson and a new pseudoscalar Higgs boson decaying into a pair of DM particles.

6. Higgs-to-invisible search

The search for invisible decays of a Higgs boson produced via the vector-boson fusion process, using 20.3 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV, is reported in [14]. The target signature in this analysis is two jets and large $E_{\mathrm{T}}^{\mathrm{miss}}$. No excess is observed and exclusion limits are set. The results are interpreted in Higgs-portal Dark Matter models, where the limit on the branching ratio is converted into upper bounds on the χ-nucleon scattering cross section, and compared to results from the direct DM detection experiment.

7. Associated production of DM with heavy flavour quarks

Searches for DM in association with heavy flavour quarks are motivated by the fact that in many models the interaction strength between the DM and the quarks is proportional to the quark masses, leading to better sensitivity for searches explicitly requiring heavy quarks in the final state. Searches for the $E_{\mathrm{T}}^{\mathrm{miss}} + t\bar{t}$ signature under the assumption of a simplified model with Dirac DM particles and a scalar or pseudoscalar mediator are performed using 13.2 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV and are targeting hadronic, semi-leptonic and di-leptonic decays of the top quarks [9–11]. The signature in the semi-leptonic analysis contains four jets, two of which are b-jets, one lepton and large $E_{\mathrm{T}}^{\mathrm{miss}}$. In this analysis the largest deviation from the SM background predictions is observed in the signal region DM_low with a local significance of 3.3 σ. The dominant background processes are $t\bar{t}$, Wt, $t\bar{t} + Z(\to \nu\nu)$ and W+jet.

8. Conclusion

A variety of searches for DM production has being performed by the ATLAS Collaboration. The searches target signatures with additional visible objects, such as jets, gauge bosons, Higgs bosons and heavy quarks. The SM predictions are consistent with the observed data in all search channels. Exclusion limits are placed on the masses of the DM particles, the masses of

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the mediators in simplified models, the suppression mass scale M_* in EFT models, as well as on the χ-proton scattering cross section. The ATLAS limits are complementary to the results from the direct DM detection experiments.

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