Search for dark matter with the ATLAS detector

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Abstract: This paper presents the results of several searches for dark matter with the ATLAS experiment at Large Hadron Collider using proton–proton collisions at $\sqrt{s} = 8$ TeV. These include searches for events with large missing transverse momentum and a photon, a single jet or $W/Z$ boson. Both hadronic and leptonic $W/Z$ decays are considered. In a number of models, the dark matter particles can be produced in association with heavy flavour (top or b-quarks). Results of these searches are summarised.

Keywords: ATLAS; LHC; CERN; high energy physics; dark matter; monojet; WIMP; monophoton; heavy flavour

1. Dark matter with standard model vector bosons

The origin of dark matter is one of the outstanding questions in contemporary physics. Collider experiments such as ATLAS are sensitive to the pair production of the so-called WIMPs in association with an initial state radiation leading to a final state jet, photon or $W/Z$; we denote this reaction $p + p \rightarrow \chi \chi + X$, where $\chi$ is the WIMP and $X$ is either a jet, photon or $W/Z$. The $\chi$ pair escapes the detector undetected, leading to a signature of missing transverse energy ($E_{T}^{\text{miss}}$). The remaining signal characteristics are determined by the nature of $X$. In this paper, quantities such as missing transverse energy and transverse momentum are given in vector notation when their direction matters ($E_{T}^{\text{miss}}$ and $p_{T}$) are in roman font when their magnitudes are used ($E_{T}^{\text{miss}}$ and $p_{T}$).

ABOUT THE AUTHOR

The author is involved in the analysis of data from the ATLAS experiment since 2010, and in particular in the search for Supersymmetry, weakly produced supersymmetric particles and search for dark matter using the so-called monojet final states. The work presented here is a summary of recent searches performed by the ATLAS Collaboration, relevant to the search for dark matter using the so-called monojet, monophoton, mono-$W/Z$ and mono-top final states.

PUBLIC INTEREST STATEMENT

Astrophysical and cosmological measurements show that our universe must contain a large quantity of matter that does not interact with light and is therefore “invisible” or “dark”. This matter is called dark matter. Today’s best explanation for this dark matter is that it is made of particles that interact weakly like neutrinos but that are relatively heavy, perhaps hundred times heavier than a proton. Such a particle is called weakly interacting massive particle (WIMP). One problem is that there is no known elementary particle that has the properties of a WIMP, therefore it must be a new, and yet an unknown particle.

The large hadron collider (LHC) at CERN collides protons at sufficiently high energy that it could produce dark matter WIMPs if they exist. The difficulty lies in finding the WIMPs among billions of recorded particle collisions. The ATLAS experiment has been used to examine the collisions and look for the WIMP particles in several possible experimental signatures.
ATLAS examined the case where $X$ is a photon (ATLAS Collaboration, 2015a) by selecting events with a photon in the central region of the detector defined by $|\eta_{\gamma}| < 1.37$, with high transverse momentum $p_{T,\gamma} > 125$ GeV and high missing transverse energy $E_{T}^{\text{miss}} < 150$ GeV. The photon is required to be away from the missing energy direction in the transverse plane $\Delta \phi (\gamma, E_{T}^{\text{miss}}) < 0.4$. At most one hadronic jet is permitted in these events, while events with electrons above 7 GeV or muons above 6 GeV of transverse momentum are vetoed. The absence of excess in the signal region is used to derive upper limits on the production of dark matter particles together with a final state photon. The experimental result is interpreted in the framework of an effective field theory (EFT); the complete list of allowed effective operators is given in Goodman et al. (2010). Here, the case where the WIMP is a Dirac particle is investigated. The EFT operators that can be constrained by this analysis correspond to a spin-1 mediator with a vector coupling (D5), an axial-vector coupling (D8) and tensor interaction (D9). The other parameters of the EFT are the so-called suppression scale $M^*$ and the mass of the WIMP $m_{\chi}$. The effective theory is only valid if the momentum transfer in the elementary process $Q_{\text{tr}}$ is smaller than the mass of the particle mediating the interaction $m_{\nu}$. In the EFT, $m_{\nu}$ is integrated away and is not an explicit parameter of the theory. If the coupling of the mediator particle to the standard model fermions is written $g_f$ while $g_{\gamma}$ is its coupling to the WIMP, then the EFT validity condition is written $Q_{\text{tr}} < M^* \sqrt{g_f / g_{\gamma}}$. In order to evaluate the effect of this condition on the ATLAS limits on dark matter, one can re-evaluate the limits on dark matter using the conservative assumption that ATLAS simply has no sensitivity to dark matter events in which the EFT validity condition is broken, the $Q_{\text{tr}}$ distribution is truncated to remove dark matter signal events above the validity limit. The fraction of dark matter signal events that are truncated depends on the value of $\sqrt{g_f / g_{\gamma}}$, thus two cases are considered: $\sqrt{g_f / g_{\gamma}} = 1$ and $\sqrt{g_f / g_{\gamma}} = 4\pi$, also referred to as max coupling. Figure 1 shows the ATLAS limits based on the single-photon signal region, without truncation and with the two truncation scenarios for the EFT operators D5, D8 and D9. Limits on $M^*$ up to 760 GeV (D5, D8) and up to 1 TeV (D9) are obtained. The effect of the truncation is small in the case of D9 but can be strong in the case of max coupling for operators D5 and D8. Upper limits on the WIMP–nucleon spin-dependent and spin-independent cross-sections are inferred and also shown in Figure 1.

The absence of excess in ATLAS data in the high transverse momentum photon signal region is also interpreted in the framework of a simplified model where the WIMP production at LHC is mediated by a heavy spin-1 vector boson. The model parameters are the WIMP mass $m_{\chi}$, the mediator mass $m_{\nu}$.
the mediator width $\Gamma$ and the coupling $\sqrt{g^2 g'}$. Figure 2 shows the upper limit on $\sqrt{g^2 g'}$ in the case $\Gamma = m_T/3$. The shaded area in the upper left corner corresponds to models that would provide relic dark matter densities larger than those allowed by cosmological measurements and is thus excluded. The ATLAS’s high transverse momentum photon signal region is finally used to set limits on a model where dark matter is produced at LHC via an effective theory $\gamma \gamma \chi \chi$ vertex (Nelson, Carpenter, Cotta, Johnstone, & Whiteson, 2014). The model parameters are the coupling strength of the WIMP to the $U(1)$ and $SU(2)$ gauge bosons, $k_\gamma$ and $k_Z$, and the suppression mass scale $M^*$. Figure 2 shows the lower limits on the suppression scale $M^*$ in this scenario. The shaded area corresponds to models where the relic dark matter density provided by the model would be inconsistent with other experimental observations considered in Nelson et al. (2014).

In the case of boosted and hadronically decaying $W/Z$ (ATLAS Collaboration, 2014a), the two daughter quarks are boosted and yield a large cone jet. The large jet is reconstructed using the Cambridge–Aachen algorithm (Dokshitzer, Leder, Moretti, & Webber, 1997) of size $\Delta R = 1.2$, with transverse momentum $p_T > 250$ GeV and $|\eta| < 1.2$. It is required that two anti-$k_T$ jets of size $\Delta R = 0.4$ are also found inside the large cone jet and that the transverse momentum is distributed between them as expected from $W/Z$ decays, this is ensured by $\frac{\min(p_T, p_T')\Delta R}{m_m} < 0.4$, where $m_m$ is the invariant mass of the two small jets, and $p_T$ and $p_T'$ are their momenta and $\Delta_R$ is the inter-jet distance. Finally, for consistency with a $W/Z$ decay, $50 < m_{jet} < 120$ GeV is required. A veto is applied against leptons, photons and light jets. Two signal regions are defined with $E_T^{miss} < 350$ and 500 GeV.

In the case of leptonically decaying $W$ (ATLAS Collaboration, 2014b), a single electron (muon) with $p_T > 125$ GeV (45 GeV) is required. The same lepton-dependent selection cut value is applied on the $E_T^{miss}$. The final discriminating variable is the transverse mass $m_T = \sqrt{2p_T E_T^{miss}(1 - \cos \phi_{\ell\nu})}$, where $\phi_{\ell\nu}$ is the distance in the azimuthal angle $\phi$ between the charged lepton and the direction of $E_T^{miss}$. Several signal regions are used with different thresholds on $m_T$, but start to be sensitive to new physics at $m_T > 252$ GeV.

If the associated boson is a $Z$ decaying into two charged leptons (ATLAS Collaboration, 2014c), the identification of the final state relies on the presence of two same flavour leptons denoted $l$ (electrons or muons), with $p_T > 20$ GeV and an invariant mass within 10 GeV of the $Z$-boson mass, and $|\eta|$ of the dilepton system less than 2.5. The dilepton system is required to balance their momenta and magnitude, with $\Delta \phi_{l\nu l\nu} = (p_T^{l\nu l\nu}) < 2.5$, where $p_T^{l\nu l\nu}$ is the transverse momentum of the dilepton system and $|E_T^{miss} - p_T^{l\nu l\nu}| < 0.54$. The final discriminating variable defining the signal regions is the $E_T^{miss}$ which is required to be above a lower threshold of 150, 250, 350 and 450 GeV, thus defining four regions.
The results from ATLAS dark matter searches are translated into upper limits on the WIMP–nucleon cross-section as function of the WIMP mass ($m_X$) in Figure 3 using an EFT approach (Goodman et al., 2010), in the case of spin-independent (left panel) and spin-dependent interactions (right panel).

2. Dark matter with heavy flavour

In a number of models, a single top quark can be produced in association with missing energy arising from the presence of a single stable or metastable particle that could be interpreted as a dark matter candidate or “top+dark matter”. ATLAS considered two scenarios (ATLAS Collaboration, 2015b) one in which the production is resonant via a coloured scalar resonance $S$ which decays into a top quark and a spin-1/2 colour singlet fermion $f_{\text{met}}$. In the second scenario, the production considered is non-resonant and leads to the production of a colour singlet spin-1 boson labelled $\gamma_{\text{met}}$. Two signal regions are designed for the two production modes. Both signal regions rely on the semi-leptonic decay of the top quark, thus requiring one isolated lepton ($e$ or $\mu$) with $p_T > 30$ GeV; the presence of exactly one $b$-tagged jet with $p_T > 25$ GeV is also required together with $E_{\text{T}}^{\text{miss}} < 35$ GeV. To reduce the background from $W$+jets and multijet processes, it is also required that $m_T + E_{\text{T}}^{\text{miss}} < 60$ GeV. Signal Region I is targeted at resonant production and requires $m_T > 210$ GeV and $\Delta\phi(\ell, b) < 1.2$, while Signal Region II requires $m_T > 250$ GeV and $\Delta\phi(\ell, b) < 1.4$. The dominant background in these signal regions is single top and top pair production. The ATLAS data are observed to agree well with the background-only hypothesis, and are thus used to set limits on the considered...
Figure 5. ATLAS upper limits on the WIMP–nucleon cross-sections in the spin-independent case via the D1 EFT operator (left) and in the spin-dependent case via the D9 EFT operator (right), as function of the WIMP mass $m_f$.

models. Figure 4 shows the upper limits on the visible production cross-sections in the resonant and non-resonant scenarios as function of the stable invisible particle masses $m(f_{\text{met}})$ and $m(v_{\text{met}})$. In the resonant case, effective coupling strengths $a_{\text{res}} > 0.15$ are excluded for $m(f_{\text{met}})$ between 0 and 100 GeV. In the non-resonant scenario, effective couplings above $a_{\text{non-res}} > 0.1$ (0.2 and 0.3) are excluded for $m(v_{\text{met}})$ up to 432 GeV (657 and 796 GeV, respectively).

Associated production of a pair of WIMPs together with a single $b$-quark or a pair of top or $b$-quarks is possible via EFT operators D1, C1 and D9 (Lin, Kolb, & Wang, 2013). The coupling strength in the case of the D1 and C1 operators is proportional to the mass of the quark at the vertex and is thus heavily suppressed for light quarks. Final states with heavy quarks are therefore an important probe of the D1 and C1 operators. ATLAS developed four signal regions (ATLAS Collaboration, 2015c) to address this scenario. The four signal regions labelled SR1 to SR4 are designed to cover the various scenarios with either $b$-quarks or top-quarks, final states with up to 2 jets or more than 3 jets, and cases where both top quarks decay hadronically versus the case where one of the top quarks decays semileptonically. The ATLAS data agree well with the background-only hypothesis in all four signal regions. For the final dark matter limits, the signal region providing the best expected sensitivity is selected and depends on the EFT operator considered. As in the case of the single high transverse momentum photon signal region, the limit of validity of the EFT is considered; here, the maximum coupling scenario is adopted. Figure 5 shows the upper limit on the spin-independent and spin-dependent WIMP–nucleon cross-sections as function of the WIMP mass $m_f$.

ATLAS also considered the model proposed to explain excess of $\gamma$-rays from the galactic centre, recently observed by Fermi satellite, and interpreted as a signal for DM annihilation in Agrawal, Batell, Hooper and Lin (2014). In this model dark matter has bottom flavour and could be produced at LHC in association with $b$-quarks via a new scalar field $\phi$. For $m_f = 35$ GeV as suggested by the FERMI signal at the galactic center, mediator masses between 300 and 500 GeV are excluded at 95% CL.

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