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Searches for Direct Production of Dark Matter at the LHC

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Abstract. This article reports on searches for new phenomena through direct production of dark matter (DM) particles at the LHC. Searches for DM made public by Summer 2015 by the CMS [1] and ATLAS [2] collaborations, are presented and categorized according to the event topology characteristics. The data collected in proton-proton collisions at a center-of-mass energy of 8 TeV, correspond to an integrated luminosity of 19.7 fb$^{-1}$ and 20.3 fb$^{-1}$ for CMS and ATLAS respectively. The analyses find no excess of events above the Standard Model expectations and the results are interpreted in terms of 90% confidence limits on the DM-nucleon scattering cross-section, as a function of the DM particle mass, for both spin-dependent and spin-independent scenarios. We find that LHC collider searches provide a complementary probe of WIMPs to direct detection experiments, and give strong constraints on light DM particles.

INTRODUCTION

The existence of dark matter in the Universe is highly motivated by many astrophysical and cosmological observations. However, nearly nothing is known of its underlying particle nature. One of the best motivated candidates for a DM particle is a weakly interacting massive particle (WIMP) which is expected to couple to standard model (SM) particles through a generic weak interaction. Such a new particle would result in the correct relic density values for nonrelativistic matter in the early universe, as measured by the PLANCK [3] and WMAP [4] satellites.

Weakly interacting massive particles are one such class of particle candidates that can be searched for at the LHC. Because WIMPs interact so weakly that they do not deposit energy in the calorimeter, their production leads to signatures with missing transverse momentum, the magnitude of which is called $E_T^{miss}$. Here, WIMPs are assumed to be produced in pairs and the events are identified via observation of large $E_T^{miss}$ recoiling against a visible final-state object X, which may be a hadronic jet, photon, or W/Z boson. The interaction of WIMPs with SM particles is described using an effective field theory (EFT) approach, as a contact interaction mediated by a single new heavy particle or particles with mass too large to be produced directly at the LHC (see fig. 1). Such interactions can be described by contact operators with:

$$L_{int} = C (\bar{q} \Gamma q)(\bar{\chi} \Gamma \chi)$$

where C represents the coupling constant, which usually depends on the mass of the DM particle, $m_\chi$, and the effective mass scale of the interaction, $M_\ast$, and the operator $\Gamma$ describes the type of the interaction, including scalar ($\Gamma = 1$), pseudoscalar ($\Gamma = \gamma^5$), vector ($\Gamma = \gamma^\mu$), axial vector ($\Gamma = \gamma^\mu \gamma^5$) and tensor interactions. In this formalism, EFT provides a framework for comparing LHC results to existing direct or indirect DM searches. However, although the EFT approach is more model-independent, it is not valid when the typical momentum transfer approaches the scale of the high-mass particles that have been integrated out. For this reason, the pair production of WIMPs is also investigated within the so-called simplified models [5], where a pair of WIMPs couples to a pair of quarks explicitly via a new mediator particle. Simplified models do not suffer from the concerns related to EFT, but include more assumptions by design and are therefore less generic. The two approaches are thus complementary and both are considered here.
THE MONO-JET SEARCH

Events with an energetic jet and large missing transverse momentum in the final state constitute a clean and distinctive signature in searches for production of dark matter particles at colliders. Such signatures are referred to as monojet-like. In this section we describe the relevant search [6] which uses 20.3 fb$^{-1}$ of $\sqrt{s} = 8$ TeV data collected in 2012 with the ATLAS detector at the LHC. The expected background to the monojet-like signature is dominated by $Z(\to \nu\bar{\nu}) + \text{jets}$ and $W + \text{jets}$ production (with $W(\to \tau\nu) + \text{jets}$ being the dominant among the $W + \text{jets}$ backgrounds), and includes small contributions from $Z/\gamma^* (\to \ell^+\ell^-) + \text{jets}$ ($\ell = e, \mu, \tau$), multijet, $t\bar{t}$, single-top, and diboson ($WW, WZ, ZZ, W\gamma, Z\gamma$) processes.

Monojet-like topologies in the final state are selected by requiring to have at least one jet with $p_T > 20$ GeV, no leptons, whereas the leading-jet $p_T$ and the $E_T^{\text{miss}}$ satisfy $p_T/E_T^{\text{miss}} > 0.5$. Nine signal regions (SRs) are considered with increasing missing transverse momentum requirements between $E_T^{\text{miss}} > 150$ GeV and $E_T^{\text{miss}} > 700$ GeV. The main irreducible backgrounds of the analysis, namely the $W + \text{jets}$ and $Z(\to \nu\bar{\nu}) + \text{jets}$ backgrounds, are estimated using Monte Carlo (MC) event samples normalized using data in selected control regions. The remaining SM backgrounds from $Z/\gamma^* (\to \ell^+\ell^-) + \text{jets}$, $t\bar{t}$, single top, and dibosons are determined using MC simulated samples, while the multijet background contribution is extracted from data.

The data observed in the different signal regions are compared with the SM expectations for the total number of events in the different signal regions and a very good agreement is found. These results are translated into limits on the pair production of WIMPs. The $M_*$ limits for a scalar and vector type of operator within the EFT approach are shown in Figure 2 down to WIMP masses of 10 GeV, as extracted from the signal regions that exhibit the best expected sensitivity.
DM SEARCHES IN MONO-OBJECT (V/JET) + MET TOPOLOGIES

The canonical “monojet” search strategy presented in the previous section, provides model-independent means of exploring scenarios where production of DM particles proceeds via a mediator with couplings to the SM. Related mono-V (V=W/Z) searches target the associated production of DM with SM vector bosons, which can be enhanced in theories with non-universal DM couplings.

Monojet and hadronic mono-V channels

This search targets the hadronic decay modes of the vector bosons in the mono-V channels. The CMS analysis [7] explores the mono-V production at high boost utilising recently developed techniques designed to exploit information available in the sub-structure of jets. The analysis incorporates both monojet and mono-V final states in a combined search, categorized according to the nature of the jets in the event. The DM signal extraction is performed by considering the shape of the $E_T^{miss}$ distribution in each event category, which potentially provides improved sensitivity compared to the previous monojet analysis. The signature of monojet and hadronic mono-V production is a large value of missing $E_T^{miss}$ recoiling against jets. The largest backgrounds are due to Z+jet production in which the Z decays to neutrinos, and leptonically decaying W+jet production where the charged lepton falls outside of the detector acceptance or fails the reconstruction criteria, thus producing real $E_T^{miss}$.

The presence of a signal is searched for by an excess of events with respect to the expectations for the SM backgrounds in a region at high missing transverse energy. The accuracy with which the shapes for the major backgrounds (V+jets) is estimated is an essential part of this analysis. Data from control regions are utilised in order to determine both the shape and normalization for the V+jets backgrounds in the signal region. The comparisons between data and background in the $E_T^{miss}$ distributions, for each of the event categories, show a very good agreement between the expected SM backgrounds and data, at the percent level. The results of this analysis are interpreted in terms of upper limits on the DM pair-annihilation cross-section. Within the EFT approach, for a vector mediator, the direct-detection bounds dominate above $m_\chi = 6$ GeV, while for the axial-vector, scalar, pseudo-scalar mediator models, the bounds from this analysis dominate over the whole region.

The corresponding ATLAS analysis [8] identifies “large-radius” jets which are supposed to capture the hadronic products of both quarks from W or Z boson decay. Two signal regions are defined by two thresholds in $E_T^{miss}$: 350 and 500 GeV. The three irreducible backgrounds are estimated by extrapolation from a common data control region in which the selection is identical to that of the signal regions except that the muon veto is inverted and W/Z+jets with muon decays are the dominant processes. The data agree well with the background estimate for each $E_T^{miss}$ threshold. Exclusion limits are set on the dark matter signals using the CLs method. Figures 3 and 4 show direct-detection bounds at 90% confidence level vs $m_\chi$.

Leptonic mono-V channels

Further CMS and ATLAS analyses ([9] and [10] respectively) assume the scenario of a Z boson recoiling against two DM particles, where the Z boson subsequently decays into two leptons producing a clean dilepton signature along with missing transverse energy.

The relevant CMS analysis selects events with exactly two well-identified, isolated leptons with the same flavor and opposite charge ($e^+e^-$ or $\mu^+\mu^-$) with $p_T > 20$ GeV each and invariant mass within ±10 GeV of the nominal mass of the Z boson. The final selection is optimized for DM signals to obtain the best expected limit at 95% confidence level using the variables: $E_T^{miss}$ and $\Delta\phi(ll, E_T^{miss})$ among others. The ZZ and WZ backgrounds are modeled using MC simulation whereas remaining non-resonant backgrounds are estimated via data-driven methods. It is worth mentioning that the dominant background, $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$, contributes the largest theoretical uncertainties which are derived from generator differences. After a preselection of events, the distribution of $E_T^{miss}$ shows a good agreement between data and background prediction in both the di-e and di-\mu channels.

Figures 3 and 4 show combined upper limits at 90% CL which are set on the DM-nucleon scattering cross sections as a function of DM particle mass for both spin-dependent and spin-independent cases, as reported by the CMS and ATLAS analyses respectively. These limits are less stringent than the lower limits for dark matter candidates recoiling against a W or Z boson decaying to hadrons which are also shown superimposed.
FIGURE 3: The 90% CL upper limits on the DM-nucleon cross section as a function of $m_\chi$ for left: spin-dependent limits for axial-vector and tensor coupling of Dirac fermion DM candidates, and right: spin-independent limits for vector coupling of complex scalar and Dirac fermion DM candidates. Taken from Ref. [9].

FIGURE 4: Observed 90% C.L. upper limits on the DM-nucleon scattering cross section as a function of $m_\chi$ for left: spin-independent and right: spin-dependent effective operators mediating the interaction of the dark matter particles with the qq initial state. Taken from Ref. [10].

DM SEARCHES IN HEAVY-FLAVOR TOPOLOGIES

Previous monojet search results have shown that the exclusion limits for a scalar type of interaction is the least stringent among all types which have been probed. This is because in this interaction the coupling strength is proportional to the mass of the quark. As a consequence, couplings to light quarks are suppressed and inclusive monojet searches are not optimal. It is therefore expected that the sensitivity for the scalar interaction can be improved by searching for final states with third generation quarks.

The presented CMS analysis [11] searches for the associated production of dark matter particles with a pair of top quarks in the single-lepton channel. The dominant standard model background processes for this analysis are production of $t\bar{t}$+jets, $t\bar{t}$+g/W/Z, W+jets, single top, di-boson (WW, WZ and ZZ) and Drell-Yan. Signal events are selected by requiring exactly one identified isolated lepton, at least three jets and at least one b-tagged jet. Additional requirements on $E_T^{miss} > 320$ GeV and the transverse mass $M_T > 160$ GeV are applied to increase the discrimination of the background with respect to the signal. Standard model backgrounds for this analysis are estimated from simulation, with data-to-simulation scale factors applied to the dominant backgrounds of $t\bar{t}$+jets and W+jets.

The analysis observes no excess of events in the search region, and interpreting the results in the context of a scalar interaction between dark matter particles and top quarks, it sets lower limits on the interaction scale $M_\star$, shown in Figure 5, left, showing an improvement of at least a factor 2 with respect to the previously most stringent limits.
Figure 5, right, shows the observed 90% CL upper limits on the dark matter-nucleon cross sections as a function of the dark matter mass for the scalar operator considered. More stringent limits are obtained from this analysis compared to direct dark matter searches in the low mass region of less than about 6 GeV, which are excluded for dark matter-nucleon cross sections higher than \(1 - 2 \times 10^{-42} \text{cm}^2\), corresponding to \(10 - 20 \text{ fb}\). Comparable limits are obtained with the corresponding ATLAS analysis [12] by obtaining sensitivities of approximately \(\sigma_{\chi N}^{\text{SI}} = 10^{-42} \text{cm}^2\) for \(m_\chi = 10 \text{ GeV}\).

In the same context of scenarios that possible new particles favor coupling to massive SM particles, such as the top quark, additional searches look for mono-top events, in which a potential dark matter particle is produced in association with a top quark. The relevant CMS and ATLAS analyses ([13], [14]) report no evidence of new physics and calculate exclusion limits on the mass of dark matter candidates at 95% CL. Scalar and vectorial dark matter particles with masses below 327 GeV and 655 GeV respectively, are excluded.

**DM INTERACTING THROUGH HIGGS**

Direct observation of DM can also be searched for through the decays of the Higgs boson to invisible particles. The study of the properties of a Higgs boson discovered by the ATLAS and CMS collaborations in 2012, does not exclude a sizeable branching ratio for its decay to invisible particles. It also opens up the question of whether a Higgs-like scalar field plays an important role in describing the interaction between dark and ordinary matter in the universe. In particular, possible decays to weakly interacting particles, are predicted by many extensions of the SM, e.g. Higgs boson portal models.

The ATLAS collaboration has performed an independent search [15] for the \(H \rightarrow \text{inv.} \) decay in final states with two or more jets and large \(E_T^{\text{miss}}\), motivated by Higgs boson production in association with a vector boson \(V \) (\(V = W \ or \ Z\)): \(q\bar{q}' \rightarrow VH\). For the discovered Higgs boson at \(m_H = 125 \text{ GeV}\), an observed (expected) upper limit of 78% (86%) at 95% CL on the branching ratio of the Higgs boson to invisible particles is set. These limits are derived assuming SM production and combining contributions from VH and gluon-fusion processes.

However, if the mass of the DM particle is larger than \(m_H/2\), the invisible Higgs searches are not sensitive, and approaches such as analyses of \(H + E_T^{\text{miss}}\) events are required such as the ATLAS search cited [16]. Here, the \(H \rightarrow \gamma\gamma\) decay mode is used exclusively, as the small branching ratio is mitigated by the distinct diphoton resonance signature and the low expected number of background events with significant \(E_T^{\text{miss}}\). Limits on DM production are derived from the cross section limits at a given DM mass \(m_\chi\), and expressed as 95% CL limits on the suppression scale \(M_*(\Lambda)\) for EFT operators; see Fig. 6 for limits for a vector operator. For the lowest \(m_\chi\) region not excluded by results from searches for invisible Higgs boson decays near \(m_\chi = m_H/2\), values of \(\Lambda\) up to 60 GeV are excluded for the vector operators.
Searches for evidence for DM production have been presented in the monojet and other mono-object plus missing transverse energy topologies, using the dataset corresponding to an integrated luminosity of 19.7 fb$^{-1}$ and 20.3 fb$^{-1}$ of $pp$ collisions collected by the CMS and ATLAS detectors respectively at a center-of-mass energy of 8 TeV at the LHC. The observed data are consistent with SM expectations and the results are translated into upper limits at 90% CL on the DM-nucleon scattering cross sections as a function of the DM particle mass. Most stringent limits are obtained by the mono-jet and hadronic mono-V channels. Under the assumptions made in the EFT approach, the LHC collider DM limits are particularly relevant in the low DM mass region, and remain important over the full $m_\chi$ range covered.

**REFERENCES**