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# Dark Matter searches at ATLAS and CMS

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Among the experimental strategies for the search for Dark Matter, collider experiments provide unique sensitivity to its non-gravitational interactions with ordinary matter, for a range of Dark Matter masses between a few GeV and hundreds of GeV. We discuss the status of the main Dark Matter searches at the Large Hadron Collider by the ATLAS and CMS experiments, underlining the complementarity between searches in different final states and between collider and direct detection results.

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## 1. Searching for Dark Matter

Understanding the nature of Dark Matter (DM), in the hypothesis it is composed by weakly interacting massive particles (WIMPs) which have non-gravitational interactions with Standard Model (SM) particles, is a key part of the physics program of the Large Hadron Collider (LHC)[1]. While direct detection experiments look for the recoil of DM on radio-pure nuclei, and annihilation experiments search for evidence of DM-DM annihilation in SM particle-antiparticle systems, the LHC can produce DM in $pp$ collisions and probe its properties by studying events in which invisible particles are produced in association with a SM particle, $X$, giving rise to the so-called *mono-X* signature. LHC results prove to be complementary with respect to direct and indirect detection experiments, both in terms of enhanced sensitivity for low DM masses and in terms of experimental techniques – where the understanding of particle reconstruction performance and of reducible and irreducible SM backgrounds plays a crucial role in defining the sensitivity of collider results.

Typical extensions of the SM probed at the LHC[4, 5] involve the existence of a stable WIMP, $\chi$, whose interactions with the SM sector are mediated by an additional, heavier particle, $M$. For simplicity, most searches assume that $\chi$ is a Dirac fermion. The theoretical framework in which search results are interpreted is that of simplified models, which are defined by the kind of interaction between the mediator, SM particles and DM, by the masses $m_\chi$ and $m_M$ and by the coupling of $M$ to SM and DM particles, denoted as $g_{\rm SM}$ and $g_\chi$, respectively. If the mass splitting $m_M - m_\chi$ is high enough, such interactions can be probed in the context of effective field theories (EFT)[6], provided that the momentum transfer of the microscopic interaction is low with respect to the mass scale $m_M$. The parameters of such EFT would then be $m_\chi$ and the suppression scale $M_\star = m_M/\sqrt{g_{\rm SM} g_\chi}$.

At hadron colliders, one can test such models by looking for production of pairs of invisible particles $\chi\bar{\chi}$ in association with one or more energetic particle. For example, a typical benchmark is provided by a simplified model[7] in which DM particles are produced via $q\bar{q}$ annihilation to a $Z'$-like axial-vector mediator, which in turn decays to $\chi\bar{\chi}$. In this case, one may tag events by requiring large missing transverse momentum, $E_{\rm T}^{\rm miss}$, recoiling against one or more high-$p_{\rm T}$ jets coming from initial state radiation (ISR) from one of the two quarks (*mono-jet* signature)[8, 9]. The model is defined by the masses $m_\chi, m_M$ and by the couplings of $M$ with quarks, $g_{\rm SM}$, and with DM, $g_\chi$. Similarly, one can seek ISR of photons, $W$, $Z$ or Higgs bosons in mono-$\gamma/W/Z/H$ searches[9, 10, 11, 12, 13], which however have lower sensitivity to such particular model with respect to the *mono-jet* search.

Moreover, if the coupling $g_{\rm SM}$ is large enough, the same simplified model predicts a significant rate for the annihilation of the mediator into quark-antiquark pairs via the $q\bar{q} \to M \to q\bar{q}$ process. Results from searches for resonant production of two energetic jets[14, 15, 16, 17] can then be interpreted in the context of such model in terms of limits on $m_M$. Mono-$X$ searches turn out to be sensitive to the on-shell region $m_M > 2m_\chi$, while dijet searches extend the mono-$X$ sensivity to higher $m_M$ provided that the mediator width $\Gamma_M$ is such that the expected peak in the dijet invariant mass distribution would be narrow.

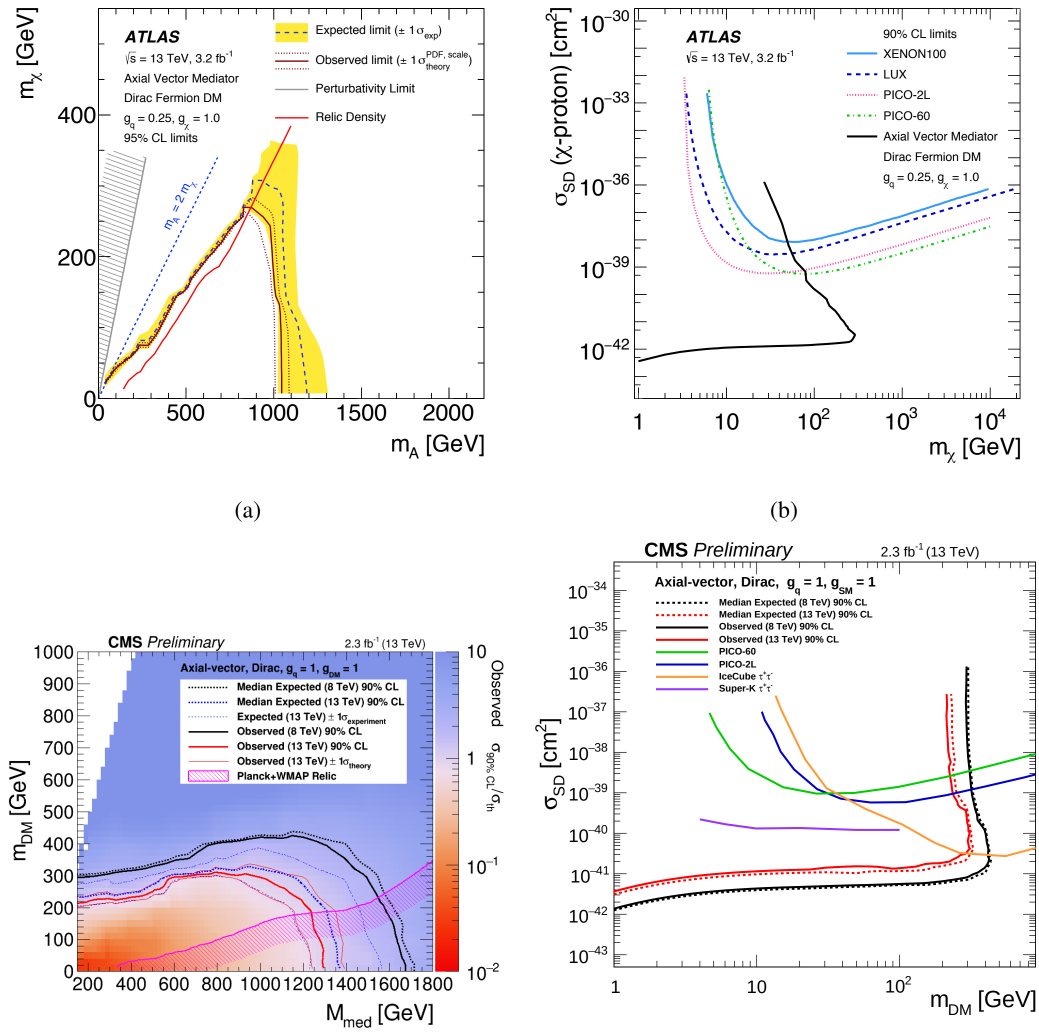
Another example is provided by a simplified model[7] in which the mediator $M$ is a scalar or pseudo-scalar particle, with Yukawa couplings to SM quarks. In this scenario, couplings with $b$ and $t$ quarks would be enhanced, leading to experimental strategies which are based on the search for events with $E_{\mathrm{T}}^{\mathrm{miss}}$ and one or more $b$ or $t$ quarks[18, 19, 20, 21]. These processes are in general more challenging to detect, as they have lower cross-sections and softer $p_{\mathrm{T}}$ spectra than the ones predicted by the $s$-channel model described above.

In the following, we briefly describe the three main paths for DM searches developed by the ATLAS[2] and the CMS[3] experiments at the LHC, and discuss their current results. A detailed description of the two experiments and of their object reconstruction techniques is provided in Ref. [2, 3].

## 2. $E_{\mathrm{T}}^{\mathrm{miss}}$ + Jet Searches

The ATLAS and CMS searches for events with high-$p_{\mathrm{T}}$ jets and large $E_{\mathrm{T}}^{\mathrm{miss}}$[8, 10, 9] in $pp$ collisions at a center-of-mass energy, $\sqrt{s}$, of 13 TeV are performed using events selected by $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger requirements, which are ensured to be fully efficient by requiring $E_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ (ATLAS) or $E_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$ (CMS). Jets are reconstructed with the anti-$k_{\mathrm{T}}$ algorithm[22], using as constituents either topological clusters of energy deposits (ATLAS) or particle-flow candidates (CMS). Different categories of jets are defined by the anti-$k_{\mathrm{T}}$ radius parameter $R$: *narrow jets* with $R = 0.4$ and *large-radius* jets with $R = 1.0$ (ATLAS) or $R = 0.8$ (CMS). Large-radius jets are additionally identified as $W$ or $Z$ boson candidates, by using tagging algorithms based on the mass and two-prong substructure of the jet. ATLAS conducts such searches with two dinstinct analyses[8, 10] which require the narrow and large-radius jet $p_{\mathrm{T}}$ to be higher than 250 GeV and 200 GeV, respectively, $E_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$, the difference $\Delta\phi(j, E_{\mathrm{T}}^{\mathrm{miss}})$ between the azimuthal angles of $E_{\mathrm{T}}^{\mathrm{miss}}$ and any narrow jet to be higher than 0.4, and veto events with reconstructed electrons or muons. CMS has a combined search strategy[9], in which events are selected either with one large-radius jet with $p_{\mathrm{T}} > 250\,\mathrm{GeV}$ and $E_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ or with at least one narrow jet with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$ and $E_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$. Similarly to ATLAS, events with one reconstructed electron, muon, $\tau$ lepton, photon or $b$-jet are vetoed, and a cut $\Delta\phi(j, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.5$ is applied. The combination between the narrow and large-radius jet channels provides a gain in sensitivity to DM signals between 2% and 5% with respect to the narrow jet analysis alone.

The dominant SM backgrounds to these searches are due to $Z$+jet production, where the $Z$ boson decays into neutrinos ($Z(\nu\nu)+$jet), and to the $W(\mu\nu)+$jet and $W(\tau\nu)+$jet processes, where a muon is not reconstructed or a $\tau$ lepton decays hadronically or into an undetected electron or muon and a neutrino. The $Z(\nu\nu)+$jet background is estimated using a semi-data-driven technique, in which a correction of the Monte-Carlo simulation (MC) is obtained as a function of $p_{\mathrm{T}}(Z)$ by using various control regions (CR) in which lepton or photon vetoes are inverted. For this purpose, the $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation in CRs is performed by considering these leptons or photons as invisible particles. In order to extract the corrections to $Z(\nu\nu)+$jet simulation, $W(\ell\nu)+$jet and $Z(\ell\ell)+$jet MC, a simultaneous binned fit to signal and control regions of the expected event yields in different bins of $E_{\mathrm{T}}^{\mathrm{miss}}$ is performed. ATLAS estimates the correction to $Z(\nu\nu)+$jet simulation by using a CR enriched in $W(\mu\nu)+$jet events, while CMS uses simultaneously the information from CRs enriched in $W(\ell\nu)+$jet, $Z(\ell\ell)+$jet and $\gamma+$jet events. The estimation of $Z(\nu\nu)+$jet from $W(\mu\nu)+$jet or $\gamma+$jet has an associated systematic uncertainty due to electroweak next-to-leading-order corrections[23], which has a dominant impact on the overall background uncertainty ($2-5\%$ effect, depending on $E_{\mathrm{T}}^{\mathrm{miss}}$). An additional contribution to the background uncertainty with a similar order




(a) (b)

(c) (d)

**Figure 1:** Observed and expected exclusion contours on the $(m_M, m_\chi)$ plane (left), for the simplified model with an axial-vector mediator, and their translation into upper limits on the spin-dependent DM-nucleon interaction cross-section (right). ATLAS results (top) use the narrow jet analysis alone[8], while the CMS results (bottom) combine the narrow and large-radius jet results[9].

of magnitude comes from the uncertainty on the modelling of the subleading $t\bar{t}$ background, which is estimated from simulation. Good agreement is observed between the estimated SM backgrounds and the data corresponding to an integrated luminosity of $3.2\,\text{fb}^{-1}$ (ATLAS) and $2.3\,\text{fb}^{-1}$ (CMS).

Search results are expressed in Figure 1(a) and Figure 1(c) in terms of 95% confidence level (CL) exclusion contours in the $(m_M, m_\chi)$ mass plane for the axial-vector simplified model, assuming values of the couplings $g_\chi = 1$ and $g_{SM} = 0.25$ (ATLAS) or $g_{SM} = 1.00$ (CMS). As it can be seen from Figure 1(b) and Figure 1(d), where these contours are translated into 90% CL upper limits on the spin-dependent DM-nucleon interaction cross-section as a function of $m_\chi$, ATLAS and CMS results provide unique sensitivity with respect to direct detection experiments for $m_\chi \lesssim 10\,\text{GeV}$. In the case of the ATLAS large-radius jet analysis, results are also expressed in Figure 2 for an effective $ZZ\chi\chi$ interaction in terms of 95% CL lower limits on the suppression scale $M_\star$ as a function of $m_\chi$.

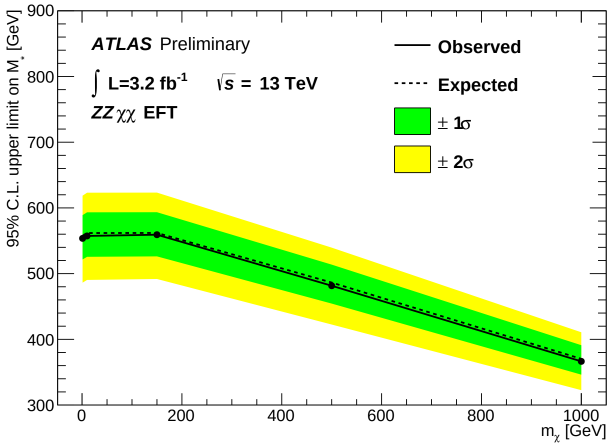



**Figure 2:** Observed and expected lower limits on the suppression scale $M_\star$ assuming an effective $ZZ\chi\chi$ interaction, for the ATLAS large-radius jet analysis[10].

Alternative search strategies in similar final states can be based on selection criteria with aim at extending the kinematic acceptance of these analyses beyond the one allowed by $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers. CMS, for example, published a search for Dark Matter at $\sqrt{s} = 8\,\mathrm{TeV}$[24] which exploits triggers and selection criteria based on *razor* variables, and a search for supersymmetry using the $\alpha_{\mathrm{T}}$ variable[25]. Both these observables provide a good separation between multi-jet background and mono-jet topologies, which is particularly relevant to reduce trigger rates, and have proven to allow access to lower energy events, particularly relevant for searches for scalar and pseudo-scalar interactions.

## 3. $E_{\mathrm{T}}^{\mathrm{miss}}$ + Heavy Quarks

Searches for scalar and pseudo-scalar interactions target final states with $b$ and $t$ quarks, whose production is enhanced due to the Yukawa structure of the interaction. The CMS search for $b\bar{b}\chi\bar{\chi}$ production at $\sqrt{s} = 13\,\mathrm{TeV}$ follows a similar strategy as for the mono-jet analysis with narrow jets[9]. Selected events are assigned to four different categories depending on the number of jets $(1,2,3)$ and of $b$-jets $(1,2)$, which allow to retain good efficiency also for $t\bar{t}\chi\bar{\chi}$ production. Control regions with 1 or 2 $b$-jets and one or two electrons or muons are used to constrain background normalisations; the dominant source of uncertainty on the background normalisation comes from $b$-tagging uncertainties ($\sim 10\%$). Search results are shown in Figure 3(c) and Figure 3(d) as a function of $m_M$, in terms of upper limits on the ratio between the observed and predicted cross-section for the scalar and pseudo-scalar model, respectively, assuming $m_\chi = 1\,\mathrm{GeV}$ and $g_{\mathrm{SM}} = g_\chi = 1$.

Searches specifically targeting $t\bar{t}\chi\bar{\chi}$ production have also been conducted both by ATLAS and CMS at $\sqrt{s} = 8\,\mathrm{TeV}$, by looking for fully leptonic (CMS[20]), semi-leptonic (ATLAS[18], CMS[21]) or fully hadronic (ATLAS[18]) $t\bar{t}$ decays. These searches make use of kinematic variables, like razor variables, able at discriminating efficiently signals from SM backgrounds with high jet multiplicities. The ATLAS search results, obtained combining the fully hadronic and semi-leptonic searches together with $b(\bar{b})\chi\bar{\chi}$ searches, are shown in Figure 3(a) and Figure 3(b) in terms of upper limits on spin-independent and spin-dependent DM-nucleon interactions, respectively, assuming scalar and tensor interactions in an EFT framework.

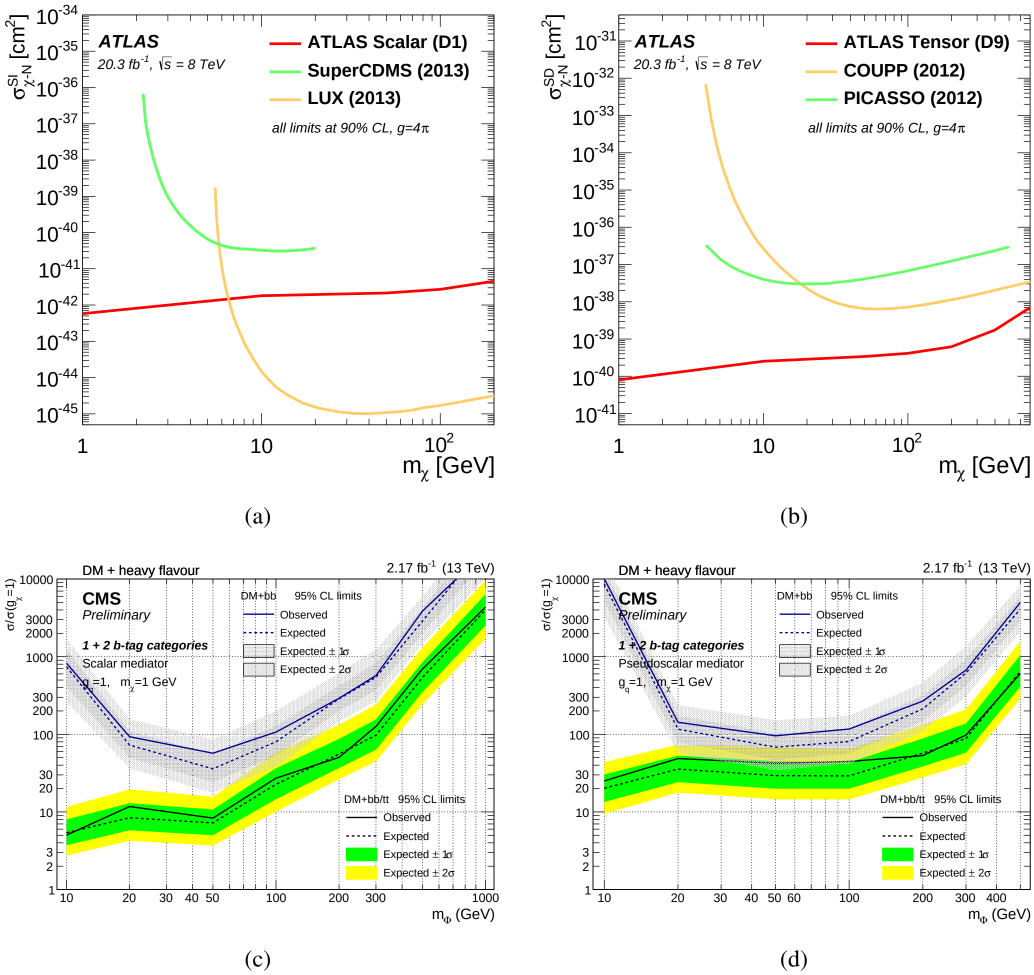



**Figure 3:** Top: observed upper limits on the spin-independent (left) and spin-dependent (right) DM-nucleon interaction cross-section as a function of $m_\chi$, obtained by the 8 TeV ATLAS search in final states with $b$ or $t$ quarks assuming scalar and tensor interactions, respectively[18]. Bottom: observed and expected upper limits on the ratio between the scalar (left) and pseudo-scalar (right) simplified model cross-section and its predicted value, expressed as a function of $m_M$ assuming $g_{SM} = g_\chi = 1, m_\chi = 1\,\text{GeV}$[19].

Additional sensitivity to specific models involving the production of a massive mediator decaying in DM plus a $t$ quark may be obtained looking for large $E_T^{miss}$ plus a large-radius jet consistent with the three-prong decay of a $t$ quark, using jet substructure techniques[26, 27, 28].

## 4. Mediator Searches

Resonances searches in dijet final states have been conducted extensively by the ATLAS and CMS experiments using $\sqrt{s} = 8\,\text{TeV}$ and $13\,\text{TeV}$ data[14, 15, 16, 17]. These searches are usually sensitive to narrow resonances with masses above $\sim 1\,\text{TeV}$, where the mass acceptance is determined mostly by the $p_{\text{T}}$ threshold of the single jet triggers used to select events. ATLAS has provided an interpretation of its dijet search results in the context of the axial-vector model, assuming $g_{\text{SM}} = 0.25$ and $g_\chi = 1$. Figure 4 shows the corresponding exclusion contours at 95% CL on the $(m_M, m_\chi)$ plane, where the slight $m_\chi$ dependence of the dijet constraints is due to the fact that the mediator width increases when approaching the on-shell region. The complementarity between dijet and mono-$X$ searches is a function of the chosen couplings: for lower values of $g_{\text{SM}}$, one expects more stringent limits from mono-$X$ searches, while for larger $g_{\text{SM}}$ dijet constraints dominate.

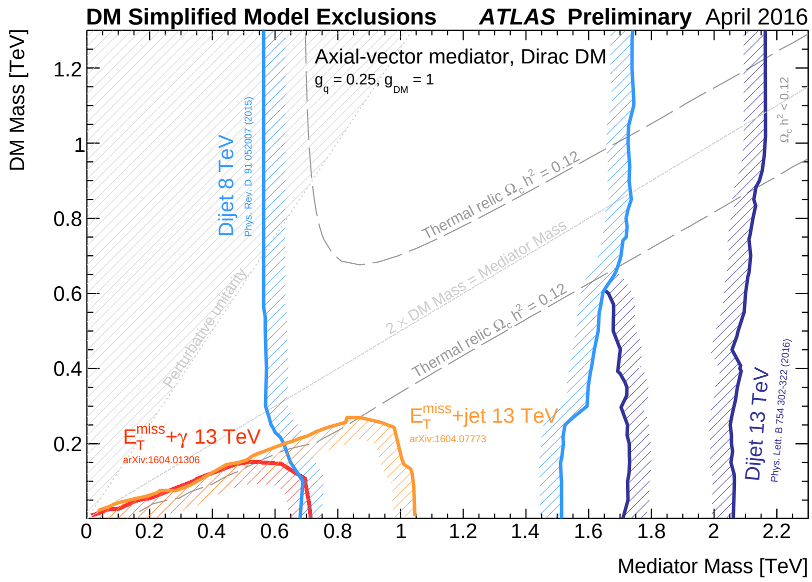



**Figure 4:** Observed exclusion contours on the $(m_M, m_\chi)$ plane for the axial-vector simplified model as obtained from the ATLAS searches in mono-jet, mono-photon and dijet final states, assuming $g_{\text{SM}} = 0.25$ and $g_\chi = 1$ [29].

Additional sensitivity to lower values of $m_M$ may be achieved using data-scouting techniques[17], for which constraints on the analysis acceptance due to trigger requirements are less stringent.

## 5. Conclusions

Searches for evidence for DM production in proton-proton collisions collected during the first LHC Run2 phase by the ATLAS and CMS collaborations have been reported. The ATLAS and CMS DM searches cover a wide range of final states all involving topologies with large $E_{\text{T}}^{\text{miss}}$ and additional objects as jets, photons, hadronic-decaying vector bosons, and heavy flavor quarks.

The observed data are consistent with SM expectations in all the channels, and upper limits at 95% (ATLAS) and 90% (CMS) CL have been set on the DM production cross section considering simplified models. These models provide a more fair description of the interaction itself and overcome the limitations of the EFT approach, which was used in Run1 by both the collaborations. The results are also translated in terms of upper limits at 90% CL on the DM-nucleon cross section as function of the DM particle mass, to compare with direct detection experiments. It is clear a complementarity of the two: collider searches are more powerful in constraining the low DM-mass region with respect to direct detection experiments for spin-independent searches where the direct detection suffers a lack of sensitivity.

Most stringent limits are obtained by the mono-jet and hadronic mono-V channels. The current results with 13 TeV are still limited by the collected statistics, but the obtained limits are compatible with the Run1 ones, even with only a sixth of the data, thanks to the increase of the analyses sensitivity. Such an improvement mainly relies on having kept high resolution and low uncertainties on the $E_{\mathrm{T}}^{\mathrm{miss}}$, the development of better background estimation methods, and the application of the most recent techniques for tagging boosted systems.

One of the limiting factors is still the online selection and reconstruction acceptance. The increase of the centre-of-mass energy and the instantaneous luminosity of LHC in Run2, and the still limited data taking conditions (detectors readout, L1 triggering systems, online event reconstruction processing time) are the main factors which force the online selection thresholds. During the long shutdown, the online event reconstruction has been optimized in order to allow the lowest thresholds and the highest resolution as possible, while keeping the rate within the allowed bandwidth. In order to exploit the current system, in addition, both experiments have developed the so-called *scouting* analyses which, reling on the online event reconstruction, can make use of lower thresholds.
The increase in the detector acceptance and the inclusion of the tracking systems in the trigger primitives, which are expected in the updgrade of both the experiments, will certainly improve the dark matter searches sensitivity.

Both collaborations plan to exploit the combination of different channels to achieve more stringent limits. In addition, the interplay between the dark matter searches and the di-jet resonances one, as it has already been proven by the ATLAS collaboration, and the Higgs boson decays into invisible as well, suggest to exploit their complementariety into a final combination and interpret it in the context of the DM framework.

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