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Searches for Dark Matter with the ATLAS and CMS Experiments using LHC Run 2 (2015–2018) Data

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The presence of a non-baryonic Dark Matter (DM) component in the Universe is inferred from the observation of its gravitational interaction. If DM interacts weakly with the Standard Model (SM) it could be produced at the LHC. The ATLAS and CMS experiments have developed a broad search programme for DM candidates, including resonance searches for the mediator which would couple DM to the SM, searches with large missing transverse momentum produced in association with other particles (light and heavy quarks, photons, Z and H bosons) called $E_{\mathrm{T}}^{\mathrm{miss}}$ +X searches, and searches where the Higgs boson provides a portal to DM, leading to invisible Higgs boson decays. The results of recent searches on 13 TeV pp collision data, their interplay and interpretation will be presented.

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1. Introduction

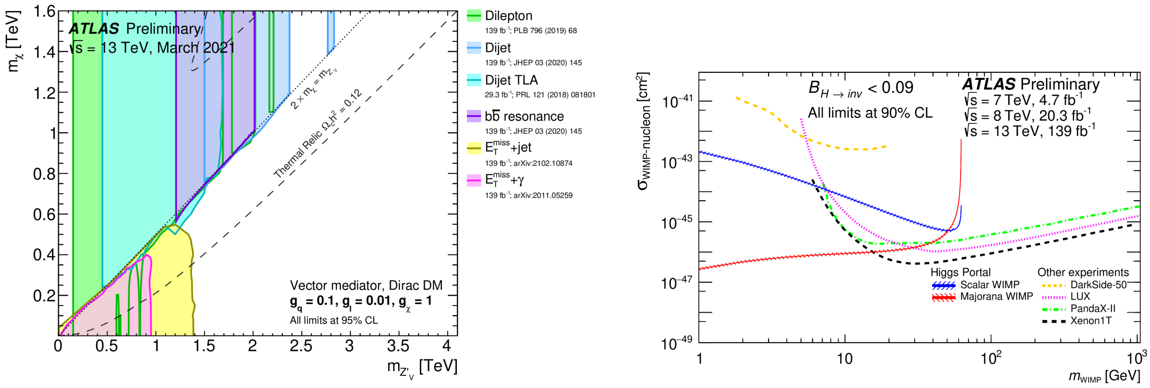
The particle nature of DM is one of the major puzzles of particle physics today. Astrophysical and cosmological evidence, for example from measurements of the cosmic microwave background, suggests that DM, a non-baryonic and non-luminous type of matter, makes up around 85% of all matter in our universe. Experiments around the world seek to unravel the nature of DM with different strategies: indirect searches look for DM in our galaxy via signs of its annihilation or decay to SM particles; direct searches are designed to detect the elastic scattering of DM off nuclei or electrons; searches at particle colliders aim to produce DM in the high-energy particle collisions of SM particles. Detectors at colliders are not directly sensitive to DM. Its existence can be inferred only indirectly via missing (transverse) momentum. Collider searches, however, are potentially sensitive to the nature of the DM–SM interaction. Assuming this interaction is mediated by new *mediator* particles, two complementary search strategies are possible: searches for *invisible* mediator decays to DM, characterised by large $E_{\mathrm{T}}^{\mathrm{miss}}$ in the final state, and searches for *visible* mediator decays that do not involve the presence of DM in the final state. In this contribution, a review of recent DM searches at the ATLAS [1] and CMS [2] experiments at the Large Hadron Collider (LHC) is presented, focusing on searches based on the $\sim$ 140 fb^{-1} datasets collected in proton-proton (pp) collisions at $\sqrt{s}$ =13 TeV during LHC Run 2 (2015–2018) and their interpretation in a variety of (non-supersymmetric) benchmark models.

2. Constraints on simplified models with an s-channel mediator

Simplified models of DM are built on a minimal set of assumptions about DM and its interaction with the SM sector and contain a minimal set of free parameters, thus providing a convenient framework to compare the results from different experiments. Invisible decays of the mediator to DM can only be detected by the trigger systems of the ATLAS and CMS experiments if an additional, visible object, for example a quark, gluon, or photon from initial-state radiation, is present in the final state, leading to a characteristic $E_{\mathrm{T}}^{\mathrm{miss}}$ $+X$ signature. Both the ATLAS and CMS collaborations have recently published various new results of searches on the full LHC Run 2 dataset, targeting the $E_{\mathrm{T}}^{\mathrm{miss}}$ +jet [3, 4], $E_{\mathrm{T}}^{\mathrm{miss}}$ $+\gamma$ [5], and $E_{\mathrm{T}}^{\mathrm{miss}}$ $+Z(\ell\ell)$ [6] signatures. These searches mostly constrain parameter regions of simplified models where $m_{\mathrm{med}} > 2 \cdot m_{\mathrm{DM}}$, as shown in Figure 1a for the case of a vector mediator. Visible decays of the s-channel mediator to a pair of quarks or leptons could be detected via searches for resonances in the dijet or dilepton invariant mass spectrum, which provide complementary sensitivity to the $E_{\mathrm{T}}^{\mathrm{miss}}$ $+X$ searches (Figure 1a). Signatures consistent with the production of a (pseudos)scalar mediator are also explored at the LHC and interpreted in simplified models. The strongest constraints on these models are derived from searches targeting the $E_{\mathrm{T}}^{\mathrm{miss}}$ $+t\bar{t}$ [7–9] and $E_{\mathrm{T}}^{\mathrm{miss}}$ $+b\bar{b}$ [10] final states and the $E_{\mathrm{T}}^{\mathrm{miss}}$ +jet final state. The most recent constraints on all simplified models can be found on the public webpages of the ATLAS [11] and CMS [12] collaborations.

3. Constraints on Higgs portal models

In Higgs portal models, the interaction between the SM and dark sectors is assumed to be mediated by the SM Higgs boson rather than a new mediator particle as in the simplified models



(a) **(b)**

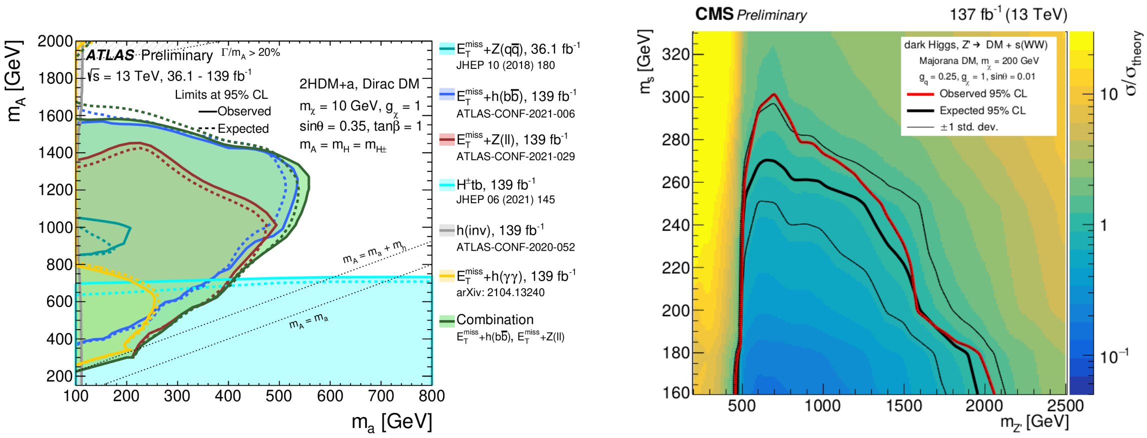
Figure 1: (a) Regions in a mediator-versus-DM-mass $(m_{Z'_V}, m_\chi)$ plane excluded at 95% confidence level (CL) by dijet, dilepton, and E_T^{miss} $+X$ searches, for leptophilic vector mediator simplified models with flavour-universal couplings of the mediator to quarks and leptons [11]. (b) Comparison of the upper limits at 90% CL from direct detection experiments on the spin-independent WIMP-nucleon scattering cross-section to the observed exclusion limits from the search in Ref. [13], as a function of the WIMP mass, assuming that the WIMP is either scalar (blue curve) or Majorana (red curve).

discussed in the previous section. This means that the Higgs boson would decay invisibly into DM with a non-zero branching ratio. In the SM, invisible Higgs boson decays occur only via the process $h \to ZZ^* \to \nu\bar{\nu}\nu\bar{\nu}$ with a branching ratio $\mathcal{BR}(h \to \text{inv.}) \approx 0.12\%$. This branching ratio can be significantly enhanced in Higgs portal models. The strongest constraints on $h \to$ inv. decays to date are derived by the ATLAS Collaboration based on a statistical combination of searches on 139 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision data targeting Higgs boson production via vector-boson fusion or in association with a pair of top quarks. These searches are statistically combined with the results of a previous statistical combination of $h \to$ inv. searches on the $\sqrt{s}$ =7 TeV and 8 TeV datasets from LHC Run 1 [13]. An upper limit on $\mathcal{BR}(h \to \text{inv.})$ of $0.11(0.11^{+0.04}_{-0.03})$ at 95% CL is observed (expected). Additionally, upper limits on the spin-independent WIMP-nucleon scattering cross-section are derived and compared to direct detection constraints for Higgs portal scenarios where the Higgs boson decays to a pair of WIMPs (Figure 1b).

4. Constraints on a two-Higgs doublet model with a pseudoscalar mediator

The two-Higgs doublet model (2HDM) with a pseudoscalar mediator (a), 2HDM+a, is the simplest and currently only gauge-invariant and UV-complete extension of the simplified model with a pseudoscalar mediator (Section 2). It is a common LHC benchmark model [15]. Pseudoscalar mediators are not strongly constrained by direct-detection experiments [16]. Unlike the simplified models described in Section 2, the 2HDM+a predicts a wide variety of possible collider signatures. For the benchmark scenarios recommended in Ref. [15], the E_T^{miss} $+h$ and E_T^{miss} $+Z$ signatures are of particular importance. The model also predicts production of DM in association with a single top quark and a W-boson at significantly higher rates compared to simplified models, inspiring a new search in the E_T^{miss} $+tW$ final state [17]. The CMS collaboration published searches on 36 fb^{-1} and 137fb^{-1} of LHC Run 2 data in the E_T^{miss} $+h(b\bar{b})$ [18] and E_T^{miss} $+Z(\ell\ell)$ [19] final states, respectively.

A comprehensive summary and combination of constraints on the 2HDM+a has been presented by the ATLAS collaboration [20]. In Figure 2a, the constraints are shown as a function of the mediator mass m_a and the mass of the pseudoscalar boson m_A The strongest constraints are provided by the E_T^{miss} $+h(b\bar{b})$ and E_T^{miss} $+Z(\ell\ell)$ searches, which are statistically combined, and a search for charged Higgs bosons $H^{\pm}$ produced in association with a top and a bottom quark ($tbH^{\pm}$), which does not probe signatures involving DM or the mediator directly, hence its constraints are mostly independent of the mediator mass.



(a) **(b)**

Figure 2: Observed (solid lines) and expected (dashed lines) exclusion regions at 95% CL (a) in the (m_a, m_A) plane of the 2HDM+a benchmark. Other free parameters are kept at fixed values: the ratio of vacuum expectation values $\tan\beta = 1.0$, the $a-A$ mixing angle $\sin\theta = 0.35$, and the DM mass $m_\chi = 10$ GeV [20]. (b) Observed (expected) exclusion regions at 95% CL for the dark Higgs model [25] in the $(m_s, m_{Z'})$ plane [23].

5. Searches for extended dark sectors

An even wider range of collider signatures is predicted in models involving more than one mediator or a more complex *dark sector*, which contains, for example, dark photons or dark Higgs bosons, in addition to one or several DM particles. A recent CMS search targets final states with *semi-visible* jets, a previously unexplored signature predicted in models with a strongly-coupled dark sector [21]. Many of these models also predict characteristic detector signatures consistent with the production of long-lived particles, discussed in other conference contributions.

Two new searches for dark Higgs bosons by the ATLAS and CMS collaborations are presented. Both target Majorana DM produced in association with a dark Higgs boson decaying to a pair of W bosons [22, 23]. The CMS search targets events with two opposite-sign isolated leptons and large E_T^{miss} , consistent with both W-bosons from the dark Higgs boson decaying leptonically. The ATLAS search targets final states with large-radius jets consistent with the boosted hadronic decays of a pair of W or Z bosons from the decay of a dark Higgs boson. The large-radius jets are built using a novel track-assisted reclustering (TAR) algorithm that combines both calorimeter and tracking information to achieve an optimal resolution of the jet substructure. Their results are interpreted and compared in the context of a common benchmark model with two mediators, a dark Higgs and

Z' gauge boson [25]. Figure 2b shows the constraints on the benchmark model as a function of the dark Higgs mass, m_s, and the Z' mass, $m_{Z'}$ with the DM mass set to $m_\chi = 200$ GeV. The mixing angle between the dark Higgs and the SM Higgs is $\sin\theta = 0.01$ and the coupling factors to the SM quark sector and DM are $g_q = 0.25$ and $g_\chi = 1.0$, respectively.

6. Conclusion

A review of the rich programme of DM searches at the ATLAS and CMS experiments has been presented, with a focus on the most recent searches using the full datasets collected during LHC Run 2. No significant excess or deficit compatible with production of DM or a DM mediator was observed to date. The results of the searches are used to constrain DM production in a range of common benchmark models, such as simplified models with an s-channel mediator, Higgs portal models, a 2HDM with a pseudoscalar mediator, and dark sector models. Many DM searches on the full Run 2 dataset, however, are still on-going and expected to become public over the next months.

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