PROCEEDINGS OF SCIENCE

Dark sector searches at ATLAS and CMS

Roberto Seidita[a,*] on behalf of the ATLAS and CMS collaborations

[a] *ETH Zürich,*
Rämistrasse 101, Zürich, Switzerland

E-mail: roberto.seidita@cern.ch

In the quest for expanding our understanding of Nature, one of the main open issues is the existence of dark matter, i.e. the observation that most of the gravitational mass acting in the Universe appears insensitive to any of the other known interactions. Collider experiments provide a powerful complement to direct and indirect searches for dark matter, both thorough searches based on simplified models aimed at exploring wide ranges of phase space, as well as more targeted searches for signatures that would elude the first strategy. We present recent results in this field from the ATLAS and CMS experiment at the CERN LHC collider.

Third Italian Workshop on the Physics at High Intensity (WIFAI2024)
12-15 November 2024
Bologna, Italy

[*] Speaker

https://pos.sissa.it/

PoS(WIFAI2024)032

1. Introduction

Searching for physics beyond the Standard Model (SM) has been a pillar of the ATLAS [1] and CMS [2] collaborations since their inception. Though no concrete sign of such new physics has emerged as of yet, the search program of both collaborations has expanded significantly to exclude larger portions of the hypothesis space. Searches for a dark sector (DS) i.e., a new set of particles and interactions (almost) separate from the SM, is complicated by the generality of such a target, which can be realized in many ways. This document is largely based on comprehensive reviews on the topic recently released by both collaborations [3, 4].

2. Mapping out the dark sector

In simple terms, a DS can be realized by any piece of Nature's lagrangian (almost) decoupled from the SM. Arguably the prime motivation for this his broad family of extensions to the SM is the observation of dark matter (DM) i.e., gravitational mass that does not interact with any of the forces described by the SM [5]. Carrying out targeted searches for each possible realization of the dark sector is prohibitive: for this reason, the framework of simplified models is often used instead. Through this strategy, a minimal number of assumption is made on the dark sector: that it contains a dark matter state (usually a fermion), and that it couples to the SM via a so-called portal particle, allowing for the production of DM states at colliders. The experimental searchs then either target the mediator as a resonance in the invariant mass spectrum of SM particles, or look for a SM object recoiling against significant missing momentum due to the non-reconstructed DM states. Although this approach is effective in setting experimental constraints on a wide range of BSM models at once, some realizations of the DS result in final states to which analysis targeting simplified models have no sensitivity. Such is the case for e.g., models with long-lived particles (LLPs) or confining DSs that produce anomalous hadronic showers. Searches for more specific DS models that result in richer final states thus complement searches in the simplified DS framework. A schematic overview of this approach is sketched in Figure 1.

3. Searches for simplified dark sectors

Both the ATLAS and CMS collaborations cover the space of simplified models extensively. This includes searches for resonances in the mass spectrum of (possibly b-tagged) hadronic jets [6–11], leptons [12, 13], or top quarks [14, 15], as well as missing momentum recoiling against hadronic jets [16, 17], vector bosons [16, 18–20], or photons [21, 22]. Interpretations are provided on a common set of benchmark models: taking the search for a vector resonance as an example, the coupling of the new vector to leptons (g_ℓ), quarks (g_q), and dark matter (g_χ) are set to either 0.01, 0.1, and 1 (leptophilic model), or 0, 0.25, and 1 (leptophobic model), respectively. Results for a leptophobic vector resonance are shown in Figure 2, with more interpretations available in [3, 4].

It is interesting to note what are the experimental limits on the reach of these searches in terms of mass of the new mediator. When the mediator mass gets too high, the statistical power of the searches is limited by the vanishing cross section of the process due to the maximum available energy in an LHC collision. When the mass of the mediator particle is low on the other hand, the

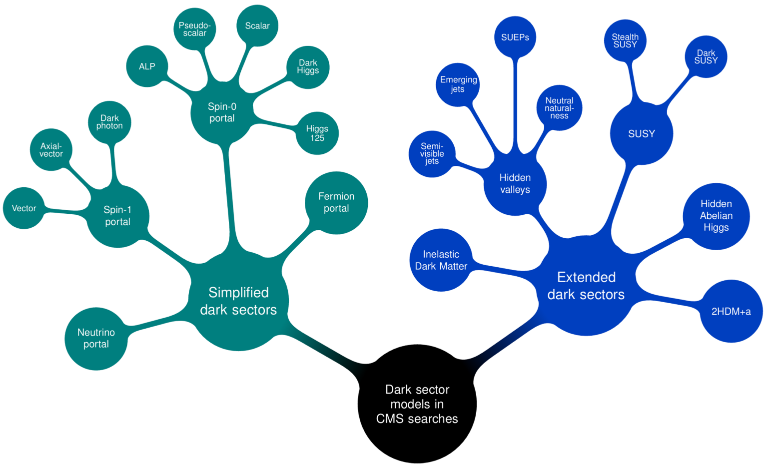

Figure 1: Schematic representation of the dual approach to DS searches at colliders, with simplified models on the left, and extended DS models on the right [4].

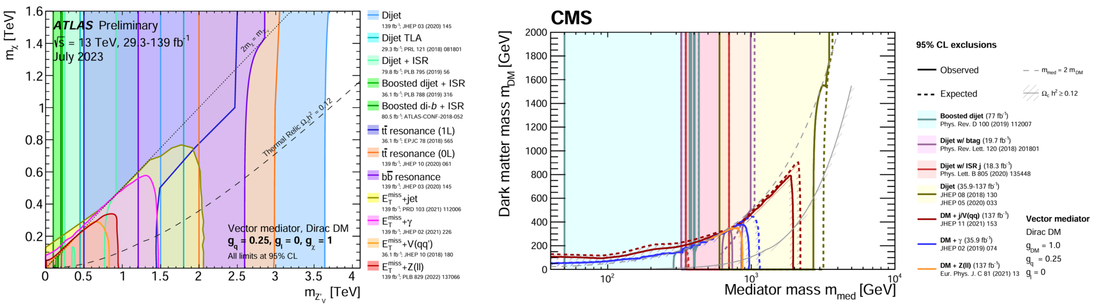

Figure 2: Exclusion limits on a leptophobic vector resonance by analyses from the ATLAS (left) [3] and CMS (right) [4] collaborations.

limit is mainly driven by the trigger systems of the two experiments. Taking the dijet resonance searches as an example, limits in the bandwitdh that the triggers can accept are reflected in a lower bound on accessible mediator masses of around 1.5 TeV. Experiments have devised strategies around this limit: by making use of additional radiation from the initial state particles, searches can target low-mass mediators with high Lorentz boost that give rise to jets with two-pronged structure; a second vector of improvement is to deploy advanced jet tagging technology directly in the trigger to e.g., select events with jets originating from the hadronization of b quarks, which are better discriminated against the overwhelming QCD-induced background, thus allowing to lower the energy thresholds without incurring in high rates; finally, a new strategy has recently been deployed by both ATLAS and CMS to overcome the limitation of the trigger system at the source via trigger level analysis [23] (TLA, ATLAS) and data scouting [24] (CMS). By leveraging the real-time reconstruction performed by the trigger to select events and storing a limited amount of information instead of the full detector readout, the per-event data size can be lowered significantly compared to storing the full information. This allows for a significant reduction of the trigger thresholds on physics objects, enabling new reach for this type of analysis. Examples of the application of this strategy to expand the reach of searches for DSs are the ATLAS TLA search for

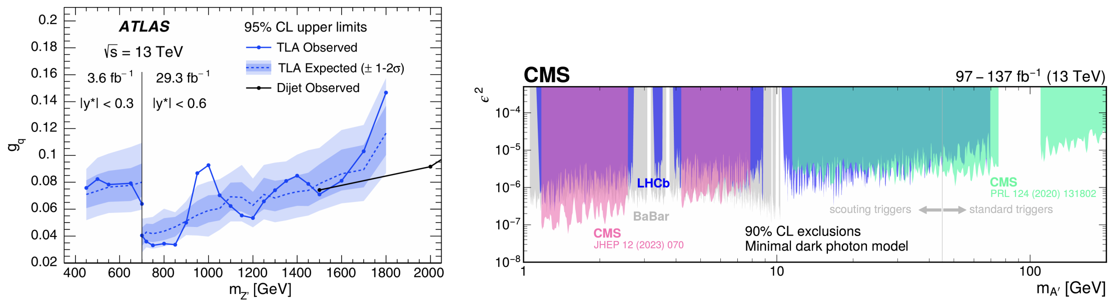

Figure 3: Exclusion map for a new vector resonance, comparing the TLA and standard searches in ATLAS (left), and exclusion map for a minimal dark photon model obtained by the CMS scouting search for dimuon resonances (right).

dijet resonances [25], expanding the exclusion reach down to almost 400 GeV compared to 1.5 TeV for the standard analysis, and the CMS data scouting search for dimuon resonances [26], which sets some of the most stringent exclusion limits to date on dark photons in the 1-10 GeV range, as shown in Figure 3.

4. Exotic final states

A second, complementary strategy to expand the reach of searches for a DS is being pursued by both collaboration by targeting exotic final states. Broadly speaking, these are final states that the standard event reconstruction and selection of ATLAS and CMS were not initially designed to catch. Such is the case when e.g., a more structured DS allows for meta-stable states: these would traverse sizable parts of the detectors before decaying back to visible objects, and because event reconstruction pipelines are mostly designed around promptly produced objects, such signatures would go undetected if not specifically searched for. The ATLAS search for long-lived dark photons [27] specifically targets jets with anomalous electromagnetic energy fraction and clusters of standalone tracks (i.e., not matched to corresponding tracks in the inner tracker) in the muon system; these objects are sensitive to dark photons decaying in the calorimeter and the muon system, respectively. A similar approach is pursued by the CMS search for inelastic DM models [28], which predict a state with long lifetime, resulting in a final state with a pair of muons originating from a displaced vertex and missing transverse momentum: leveraging tracks reconstructed only in the muon system, the search is able to extend its reach to higher lifetimes of the DM state.

Long-lived particles are not the only exotic signature that could elude standard searches for DM; another example is given by the growing number of searches for dark showers. These are the result of a confining force in the DS which, depending on the specifics of the model, can lead to a variety of experimental signatures. If the confining force in the DS is QCD-like, dark matter particles can shower and hadronize in the dark sector, forming jets of dark bound states (dark hadrons). If only a fraction r_{inv} of these is stable, the rest will decay back to SM objects, forming an anomalous jet interspersed with invisible particles, called a *semivisible* jet. The reason why this signature would elude general DM searches is precisely the fact that the invisible component in the event is aligned with the visible one, resulting in a signature of a dijet with missing momentum aligned with one of

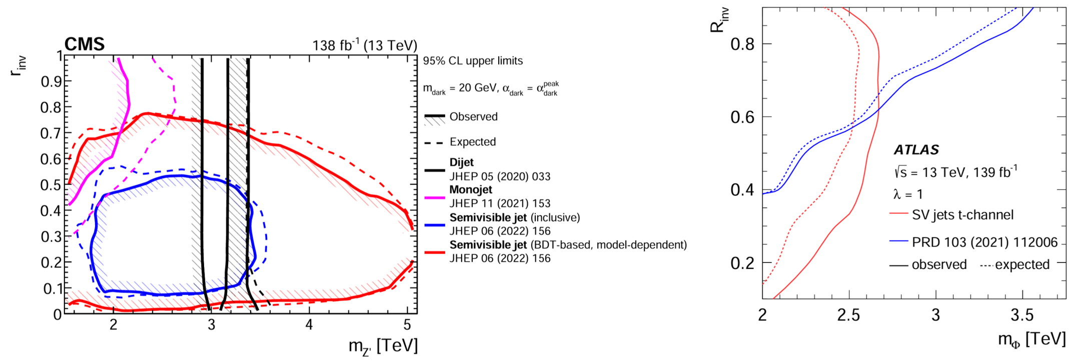

Figure 4: Comparison of the CMS (left) and ATLAS (right) searches for semivisible jets with general DM searches evaluated on the same signal hypotheses.

the jets. This even topology is explicitly excluded from searches for recoiling DM, making them insensitive to these signatures. This can be seen in Figure 4, were results of searches for resonant (CMS) [29] and non-resonant (ATLAS) [30] production of *semivisible* jets are compared to those of standard SM searches, showing how the latter are much less sensitive to this specific class of models.

If the dark hadrons produced in such fashion are long lived, the signature changes dramatically, giving rise to jets of particles originating from displaced vertices, called an *emerging* jet [31]. Finally, if the confining force in the DS is not QCD-like but e.g., in the large t' Hooft coupling regime, the resulting pattern is not jet-like but rather a diffused set of particles. This is typically referred to as a *soft unclustered* energy pattern [32].

5. Anomaly detection

To conclude this brief overview of the landscape of searches for a DS, an emerging and promising strategy is given by the use of modern anomaly detection tools. The appeal of this class of searches is in their generality: through the use of (typically) unsupervised machine learning techniques, these searches have the capability to enhance the reach of e.g., searches for dijet resonances by enriching them with information on jet substructure without making additional assumptions on specific signal models. This can be achieved by training an anomaly detection model only on the background hypothesis, and leveraging its anomaly score as a model independent observable to boost the sensitivity of the search. Two prominent examples of this strategy at work are the ATLAS search for anomalous events performed with an autoencoder [33] and the CMS search for dijet resonances with anomalous jet substructure [34].

6. Conclusions

In the quest to find traces of a dark sector, the ATLAS and CMS collaborations continue to expand their efforts by pushing traditional search methods to ultimate sensitivity, targeting previously unexplored signatures, and leveraging new tools such as unsupervised machine learning. While no evidence for a DS has been found to date, the stage is set for a thorough hunt in the years to come, powered by refined and innovative trigger strategies, event reconstruction pipelines, and analysis techniques.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3** (2008) S08003.

[2] CMS Collaboration, *The CMS Experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

[3] ATLAS Collaboration, *Exploration at the high-energy frontier: ATLAS run 2 searches investigating the exotic jungle beyond the standard model*, 2403.09292.

[4] CMS Collaboration, *Dark sector searches with the CMS experiment*, 2405.13778.

[5] A. Arbey and F. Mahmoudi, *Dark matter and the early universe: A review*, *Progress in Particle and Nuclear Physics* **119** (2021) 103865.

[6] CMS Collaboration, *Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at* $\sqrt{s}$ = *13 TeV*, *JHEP* **05** (2020) 033 [1911.03947].

[7] CMS Collaboration, *Search for low mass vector resonances decaying into quark-antiquark pairs in proton-proton collisions at* $\sqrt{s}$ = *13 TeV*, *Phys. Rev. D* **100** (2019) 112007 [1909.04114].

[8] CMS Collaboration, *Search for narrow resonances in the b-tagged dijet mass spectrum in proton-proton collisions at s=13 TeV*, *Phys. Rev. D* **108** (2023) 012009 [2205.01835].

[9] ATLAS Collaboration, *Search for resonances decaying into photon pairs in 139 fb*$^{-1}$ *of pp collisions at* $\sqrt{s}$*=13 TeV with the ATLAS detector*, *Phys. Lett. B* **822** (2021) 136651 [2102.13405].

[10] ATLAS Collaboration, *Search for boosted low-mass resonances decaying into hadrons produced in association with a photon in pp collisions at* $\sqrt{s}$ = *13 TeV with the ATLAS detector*, *JHEP* **01** (2025) 099 [2408.00049].

[11] ATLAS Collaboration, *Search for light resonances decaying to boosted quark pairs and produced in association with a photon or a jet in proton-proton collisions at* $\sqrt{s}$ = 13 *TeV with the ATLAS detector*, *Phys. Lett. B* **788** (2019) 316 [1801.08769].

[12] CMS Collaboration, *Search for resonant and nonresonant new phenomena in high-mass dilepton final states at* $\sqrt{s}$ = *13 TeV*, *JHEP* **07** (2021) 208 [2103.02708].

[13] ATLAS Collaboration, *Search for high-mass dilepton resonances using 139 fb*$^{-1}$ *of pp collision data collected at* $\sqrt{s}$ *=13 TeV with the ATLAS detector*, *Phys. Lett. B* **796** (2019) 68 [1903.06248].

[14] ATLAS Collaboration, *Search for heavy particles decaying into top-quark pairs using lepton-plus-jets events in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *Eur. Phys. J. C* **78** (2018) 565 [1804.10823].

[15] ATLAS Collaboration, *Search for $t\bar{t}$ resonances in fully hadronic final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *JHEP* **10** (2020) 061 [2005.05138].

[16] CMS Collaboration, *Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *JHEP* **11** (2021) 153 [2107.13021].

[17] ATLAS Collaboration, *Search for new phenomena in events with an energetic jet and missing transverse momentum in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector*, *Phys. Rev. D* **103** (2021) 112006 [2102.10874].

[18] CMS Collaboration, *Search for dark matter produced in association with a leptonically decaying Z boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *Eur. Phys. J. C* **81** (2021) 13 [2008.04735].

[19] ATLAS Collaboration, *Search for dark matter in events with a hadronically decaying vector boson and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *JHEP* **10** (2018) 180 [1807.11471].

[20] G. Aad et al., *Search for associated production of a z boson with an invisibly decaying higgs boson or dark matter candidates at s=13 tev with the atlas detector*, *Physics Letters B* **829** (2022) 137066.

[21] CMS Collaboration, *Search for new physics in final states with a single photon and missing transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *JHEP* **02** (2019) 074 [1810.00196].

[22] ATLAS Collaboration, *Search for Dark Matter in association with an energetic photon in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *PoS* **CORFU2021** (2022) 098.

[23] ATLAS Collaboration, *Performance of the ATLAS Trigger System in 2015*, *Eur. Phys. J. C* **77** (2017) 317 [1611.09661].

[24] CMS Collaboration, *Enriching the physics program of the CMS experiment via data scouting and data parking*, *Phys. Rept.* **1115** (2025) 678 [2403.16134].

[25] ATLAS Collaboration, *Search for low-mass dijet resonances using trigger-level jets with the ATLAS detector in pp collisions at $\sqrt{s}$ = 13 TeV*, *Phys. Rev. Lett.* **121** (2018) 081801 [1804.03496].

[26] CMS Collaboration, *Search for direct production of GeV-scale resonances decaying to a pair of muons in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *JHEP* **12** (2023) 070 [2309.16003].

PoS(WIFAI2024)032

[27] A. Biondini, *Search for light long-lived neutral particles that decay to collimated pairs of leptons or light hadrons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, other thesis, 2023-06-15, 6, 2023.

[28] CMS Collaboration, *Search for Inelastic Dark Matter in Events with Two Displaced Muons and Missing Transverse Momentum in Proton-Proton Collisions at s=13 TeV*, *Phys. Rev. Lett.* **132** (2024) 041802 [2305.11649].

[29] CMS Collaboration, *Search for resonant production of strongly coupled dark matter in proton-proton collisions at 13 TeV*, *JHEP* **06** (2022) 156 [2112.11125].

[30] ATLAS Collaboration, *Search for non-resonant production of semi-visible jets using Run 2 data in ATLAS*, *Phys. Lett. B* **848** (2024) 138324 [2305.18037].

[31] CMS Collaboration, *Search for dark QCD with emerging jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *JHEP* **07** (2024) 142 [2403.01556].

[32] CMS Collaboration, *Search for Soft Unclustered Energy Patterns in Proton-Proton Collisions at 13 TeV*, *Phys. Rev. Lett.* **133** (2024) 191902 [2403.05311].

[33] ATLAS Collaboration, *Search for new phenomena in two-body invariant mass distributions using unsupervised machine learning for anomaly detection at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *PoS* **EPS-HEP2023** (2024) 481.

[34] CMS Collaboration, *Model-agnostic search for dijet resonances with anomalous jet substructure in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, 2412.03747.