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Status and perspective of Dark Sector searches at ATLAS and CMS

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The SM of Particle Physics is the model that, up to now, best describes the matter content and its fundamental interactions. Though the tests it has gone through during the past years have always proven to confirm its validity, it still cannot provide answers for some fundamental questions, such as the nature of dark matter or the matter-antimatter asymmetry. Therefore, since the start of their physics program, large experiments such as the ones based at the LHC, like ATLAS and CMS, have looked for hints of BSM Physics. Among these kind of attempts, of particular interests are so-called *Dark Sector* searches, where the existence of a whole new sector of particles, governed by new interactions, is looked for. These searches present challenges in terms of (offline and online) reconstruction, background estimation and modelling, as they provide a very rich and unconventional phenomenology. This article reviews the most recent Dark Sector searches performed by the ATLAS and CMS collaboration, with particular focus on Dark Sector models involving the existence of a dark QED or dark QCD. Specific challenges met by the different searches are highlighted and plans to overcome them in the next LHC runs are illustrated.

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1. The ATLAS and the CMS experiments

ATLAS (A Toroidal LHC Apparatus) [1] and CMS (Compact Muon Solenoid) [2] are the largest detectors sited at the LHC (Large Hadron Collider) [3]. They are barrel-shaped with a backward-forward cylindrical symmetry around two different LHC collision points (IP, Interaction Points). They both share the same sub-structure: starting from the IP, they are comprised of an Inner Detector (ID), aimed at reconstructing tracks of charged particles, an Electromagnetic CALorimeter (ECAL), detecting electromagnetic showers of electrically charged particles, the Hadronic CALorimeter (HCAL), detecting energies of strongly interacting particles, and the Muons Spectrometer (MS), reconstructing tracks of muons. Both the CMS and the ATLAS detectors are immersed in strong magnetic fields: CMS has a 3.8 T solenoidal magnetic field while the ATLAS ID is provided with a 2 T solenoidal magnetic field and the ATLAS MS is immersed in a 1 T (0.5 T) toroidal magnetic field in the barrel[1] (endcap) region. As in the IP (populated) bunches collide at $\sim$ 33 MHz, and per every collision during Run-2 an average of 30 pp interactions occurred per bunch crossing, with roughly 200 particles per interaction produced, an online event selection is needed. The latter is aimed at selecting potentially interesting events by using a two-tiered trigger system: the $L1$ trigger, mostly-hardware based, in Run-2 reduced the event rate up to 100 kHz, and the High Level Trigger (HLT) further reduced the rate to 1 kHz. Beside these common features, the two detectors are designed in such a way to be complementary in performances: being immersed in a stronger magnetic field, the CMS detector has a better momentum resolution, both in the ID and in the MS; being an homogeneous calorimeter, CMS ECAL has a better energy resolution with respect to ATLAS one which is instead a sampling calorimeter; since a return yoke is needed for the CMS solenoidal magnetic field, the barrel HCAL has an insufficient absorption, resulting in a worse jet and missing energy E_{T}^{miss} [2] resolution with respect to the ATLAS one; relying on an independent toroidal magnetic field[3] and having a larger size, the ATLAS MS can provide a better standalone muon momentum measurement; being ATLAS twice as large as the CMS detector[4], ATLAS is better suited at detecting LLPs (Long Lived Particles) with decay lengths larger than the CMS active volume.

2. Dark Sectors

To address the SM (Standard Model) limitations, solutions involving the existence of a whole new sector of particles, called *Dark Sector* (DS) and governed by new and unkwon interactions, are investigated. In its simplest formulation, the DS can be governed by a new dark QED (Quantum-Electron-Dynamics), mediated by the so-called DP (Dark Photon), γ_d. Another possibility is the one where the new interaction is a dark QCD (Quantum-Chromo-Dynamics). In order for this new sector to be probed via its interaction with ordinary matter, a connection between the visible sector and the dark one, referred to as *portal*, has to be assumed. Different kinds of portals hypotheses have been investigated, and here the ones illustrated in this article are listed:

- the Higgs Portal (HP): the SM Higgs boson mixes with a dark Higgs boson, H_d, which analogously to the SM Higgs provides masses to the dark sector particles through Spontaneous

[1] The barrel and the endcaps are respectively the areas of the detector closer to the IP and the ones further away along the beam axis

[2] Kinematics in ATLAS and CMS are defined in the plane transverse (T) to the beam axis as the total momentum along it is unknown as a consequence of the non-fundamental nature of protons; E_{T}^{miss} is the vector sum of the p_{T} of all the objects reconstructed, taking into account also tracks which are not associated to any reconstructed particle.

[3] The CMS magentic field return yoke causes multiple scatterings of muons, reducing their momentum resolution, particularly for low p_{T} muons. This resolutuon loss is partially recovered thanks to the CMS stronger magnetic field.

[4] ATLAS (CMS) is 46 m (21 m) long, 25 m (15 m) wide and 25 m (15 m) tall.

Symmetry Breaking (SSB). This portal is of particular interest and often assumed in DS searches at colliders as Higgs boson exotic decays are still possible, since the upper limit on the Branching Ratio (BR) of the Higgs decaying into invisible particles, $BR(H \to inv)$, has been measured by the ATLAS (CMS) collaboration to be $BR(H \to inv) = 10.7\%$ [4] ($BR(H \to inv) = 15\%$ [5]);

- the Vector Portal (VP): the SM photon γ mixes kinematically with the γ_d. Through this mixing, conventionally parametrised via ε, the γ_d can decay back to visible SM particles, with BRs that depend on its mass. If this coupling is suppressed, the γ_d can acquire a large mean proper life-time, τ_{γ_d}, becoming a LLP which can even be detector stable. If the γ_d is either mass-less (or if $m_{\gamma_d} < 2m_e$, with m_e being the mass of the SM electron) or its coupling to the dark sector is larger than the one to the visible sector, its decays into SM particles are suppressed (see [6]).

These different portals as well as new interactions provide a very rich and diverse phenomenology, therefore different searches tailored on such models are carried out by both ATLAS and CMS experiments, as reviewed in Sec. 3 and Sec. 4.

3. Dark QED searches

Dark QED searches focus their attention on the mediator of the interaction itself (γ_d). According to its characteristics (its mass m_{γ_d} and its displacement τ_{γ_d}) and to the different kinds of portals involved (the VP and/or the HP), different analyses are built upon the resulting signature, as listed in Tab. 1. The ATLAS and CMS physics programs target a wide space of the free parameters of

Signature	HP	H production	VP	τ_{γ_d}	m_{γ_d} [GeV]	Search
$\gamma + E_T^{miss}$	✓	VH	✗	-	Massless	CMS [7], ATLAS [8]
		VBF				CMS [9], ATLAS [10]
jets $+E_T^{miss}$ (*monojet*)	✓	ggF	✓	Detector stable	[0.2-2]	ATLAS [11]
Displaced muons	✓	ggF	✓	Outside ID	[0.6,50]	CMS [12]
					[10,60]	CMS [13]
Displaced fermions		ggF+VBF+WH			[0.17,15]	ATLAS [14], ATLAS [15]
Prompt muon-pairs	✗	-	✓	Inside ID	[0.6,8]	CMS [16]
	✓	ggF			[0.3,10]	CMS [17]
Prompt lepton-pairs					[0.2,2]	ATLAS [18]

Table 1: Breakdown of ATLAS and CMS dark QED searches, grouped according to the signature looked for. It should be noted that [16] is the only search targeting γ_d production via Drell-Yan and that beside [18], which has been carried out during Run-1, all the others are Run-2 searches.

such DS models, exploiting very different signatures that result in very different and challenging analyses. Being the most challenging searches in terms of non-conventional final states, the searches for displaced γ_d yielding pairs of displaced muons or fermions ([12],[13][14],[15]) will be briefly illustrated in the following section.

3.1 Displaced dark photon searches

These searches all share similar final states, that are displaced, collimated, non-pointing (to the collision point) and soft SM fermions, that present challenges both at the online and the offline reconstruction level. The CMS searches [12] and [13] target only γ_d decays into muons, while the ATLAS searches [14] and [15] look for γ_d decays into electrons and light hadrons as well. The CMS search targeting low mass γ_d [12] exploits the so-called *scouting trigger strategy*. In these triggers the HLT p_T threshold is decreased, with a consequent increase in the event rate (3 kHz).

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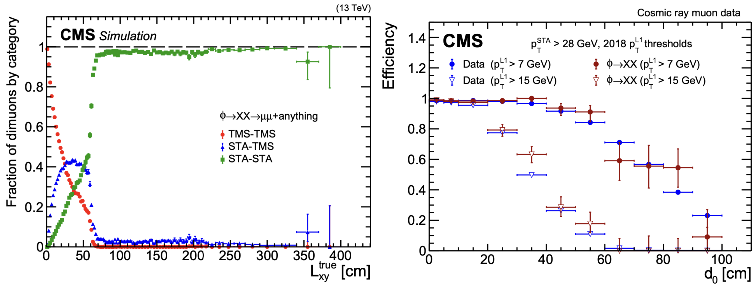
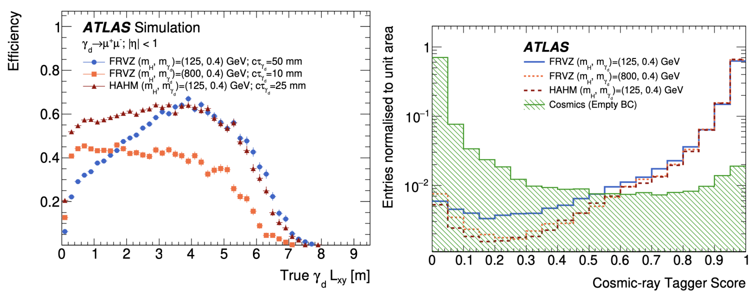
Therefore to have the same bandwidth of standard triggers, the event size needs to be reduced. By using these triggers the sensitivity to soft muons is increased, whilst requirements on a minimum number of ID hits at the HLT trigger limits the sensitivity to displaced muons. The CMS search targeting heavier γ_d [13], recovers sensitivities to displaced muons by targeting muon pairs not only when both muons are reconstructed both in the MS and in the ID (TMS muons), but also when one of them is reconstructed only in the MS (STA muon) or both of them are. In such a way, sensitivities to very large γ_d displacement L_{XY} can be achieved, as seen in Fig. 1 (a). However, L1 trigger requirements on the Beam-Spot compatibility, i.e. a small impact parameter d_0 with respect to where the pp collision occurred, decrease the sensitivity of the search when non-ponting muons are found, as it can be seen in Fig. 1 (b). The ATLAS searches [14] and [15] reconstruct each final



(a) **(b)**

Figure 1: (a): Muon pairs reconstruction efficiencies as a function of the γ_d decay length L_{XY} for different kinds of muons pairs (see text) (b): L1 muon trigger efficiency in cosmic ray muon data (blue) and signal simulation (red) as a function of d0, for the L1 trigger p_T thresholds used 2018. Plots from Ref. [12].

state collimated fermion-pair as a single object, referred to as *Dark Photon Jet* (DPJ), which can be either muonic, when it is comprised of muons, or calorimetric, when it is reconstructed only via calorimeter information (resulting either from displaced electrons or light hadrons). Fig. 2 (a) shows how μDPJs reconstruct γ_d decays within the whole ATLAS active volume. In order to distinguish unconventional backgrounds (such as comsic-rays) from possible signals, different Neural Networks (NN) are exploited: as an example signal-like μDPJs are distinguished from cosmic-ray ones using a Dense NN, whose performances are shown in Fig. 2 (b). To further increase the sensitivity of the search to displaced objects, unconventional HLT either looking for displaced collimated muon pairs or displaced jets are used. However limitations on these searches come again from $L1$ trigger



(a) **(b)**

Figure 2: (a): μDPJ reconstruction efficiencies as a function of γ_d decay length L_{XY} for different kinds of signal model tested (b): Cosmic-ray Tagger separating μDPJ arising from the cosmic-ray background (green) from μDPJ arising from different signal models. Plots from Ref. [14].

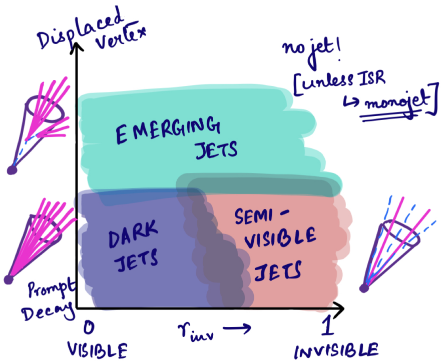


Figure 3: Schematic diagram indicating the phenomenology of dark QCD with respect to different r_inv scenarios. Picture taken from Ref. [19]

requirements, related to both the Beam-Spot compatibility and the large collimation of the final state muons, which cannot therefore be both $L1$ trigger seeds.

4. Dark QCD searches

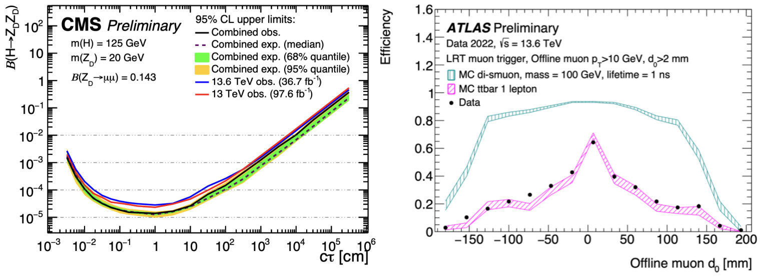
Dark QCD searches can be divided in three categories, depending on r_{inv}, the fraction of stable dark hadrons, and the displacement of the un-stable hadrons, as depicted in Fig 3. When $r_{inv} = 0$ all dark hadrons decay to SM hadrons, producing jets that therefore undergo a double hadronization, one in the dark sector and another one in the visible one. These *dark jets* show a wider structure with respect to SM jets. This scenario has been investigated by the ATLAS collaboration looking for di-jet events [20]. For larger r_{inv}, reconstructed jets are comprised of both a visible and an invisible component and are therefore called *semi-visible jets*. This scenario, targeted looking for jets with a close-by sizable E_{T}^{miss}, has been investigated by the ATLAS collaboration in the $t - channel$ [21] and by the CMS collaboration in the $s - channel$ [22]. When instead the jets are completely invisible they can be looked for using the *monojet* signature, as in [11]. If the unstable hadrons are long-lived, this would result in *emerging-jets*, which, according to the different hadrons life-times, could be trackless jets or have late calorimetric releases, as investigated by the CMS collaboration [23]. Besides experimental challenges analogous to the ones related to dark QED searches, dark QCD searches are at the moment mostly limited by the modelling of the dark QCD processes.

5. Perspective for Dark Sector searches

DS searches carried out by the ATLAS and CMS experiments are very diverse and exploits a wide range of signatures resulting in various analyses techniques. Whilst great progresses have been made, dark QED searches are at the moment mostly limited by trigger requirements while dark QCD searches by the modelling. In order to better the discovery potential of dark QED analyses, both ATLAS and CMS have loosened some trigger requirements to be sensitive to more exotic signatures. To instead overcome the limitations arising from the dark QCD modelling, a more model-independent approach is sought by both collaborations. In the following, a few examples of such studies are listed.

5.1 Auto-Encoders for Semi-Visible Jets

Auto-Encoders (AE) are NN based architecture which, by encoding into a smaller dimension the input they are given and decoding it into the initial dimension, are able to learn only the relevant



(a) **(b)**

Figure 4: (a): Excluded $B(H \to 2\gamma_d)$ as a function of τ_{γ_d} for $m_{\gamma_d} = 20\,\text{GeV}$ obtained by the Run-2 search (blue) and the Run-3 one (red), plot from Ref. [25] (b): HLT LRT performances for displaced muons (azure) arising from a BSM LLP decay and for standard muons from $t\bar{t}$ processes (pink) compared to data (black dots), plot from Ref. [26].

features of their input, by minimizing a metric which parametrises the difference between their input and their output. If trained with standard objects they can be used to tag anomalous ones, which are identified with a large reconstruction error. When however the phase space of the anomalous objects is close-by to the one associated to standard ones, the AE is still able to accurately reconstruct the anomalous objects, therefore being unable to distinguish them. As explained in [24], however, if the AE is instead trained to learn the distribution probability of the input dataset, such as top-jets in this study, anomalous objects, such as semi-visible jets in this case, are reconstructed with a large reconstruction error and are therefore correctly tagged as anomalous. Therefore AE trained in such a way are a promising tool to look for semi-visible jets with a model-independent approach.

5.2 Triggers for displaced, non-pointing, soft objects

As said in Sec. 3, dark QED searches looking for displaced objects are mostly limited by trigger requirements. The CMS collaboration improved muon trigger performances in Run-3, both at the HLT and the $L1$ trigger level. The HLT scouting trigger threshold has been further reduced, therefore enhancing the sensitivity to even softer muons. At the $L1$ trigger level, the main limitation came from the Beam-Spot compatibility requirement. The latter has been removed (for muons reconstructed in the barrel), with an increase of the reconstruction efficiency for muons with large displacement up to 80%. An early Run-3 version of the Run-2 search looking for high mass γ_d decaying into displaced muons [13], presented in Sec. 3, has been recently published [25] with these improvements, while the analysis strategy was left unchanged. As can be seen in Fig. 4 (a), whilst having a third of the Run-2 search statistics, the Run-3 search has roughly the same sensitivity, clearly indicating the impact of the trigger requirements on the analyses discovery potential. The ATLAS collaboration has instead developed the so-called *Large Radius Tracking* (LRT), a tracking algorithm which loosens the Beam-Spot compatibility requirement from $|d_0| < 10\,\text{mm}$ to $|d_0| < 200\,\text{mm}$. Whilst already running during Run-2 at the offline level only on the 20% of data as it was too computationally expensive, after improvements of both the standard tracking and the LRT it is now running at the HLT level, therefore recovering sensitivity to displaced scenarios, as can be seen by Fig. 4 (b) [26].

6. Conclusions

Dark Sectors are intriguing scenarios solving some of the fundamental questions of the SM which are still unanswered. During Run-2 many different searches have been carried out, looking for example for hints of dark QED or of dark QCD. These searches have all proven to be inconclusive, but however they paved the way to improvements on the detectors side, both at the hardware and the software level (such as the LRT and the L1 requirements changes), as well as on the analyses technique side, for example leading to more model-agnostic searches through the usage of Machine Learning. These improvements have already proven to have sizeable impact on such searches, therefore improving the discovery potential of Run-3 and future runs searches.

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