Probing Stealth Dark Sectors with LHCb

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1 The Beautifulness of Flavor

To discuss the dark matter search strategies at LHCb, it is useful to first establish the main conceptual design differences between this detector, and the previously described ATLAS and CMS experiments. These differences are due to the distinct physics goals of LHCb.

Sometimes, ATLAS and CMS are referred to as *general-purpose detectors* or *GPDs*. Their design aims at exploring higher energies than the previous generation proton-proton collider (Tevatron, in Fermilab, Batavia, USA) in an agnostic way, collecting as much data as possible, and with the aim of discovering the Higgs boson for masses above 114 GeV (the mark set by the LEP collider in the early 2000s) as well as targeting heavy particles with masses between about 100 GeV and up to a few TeV. The reasons why to expect new particles in these ranges are numerous and they would not fit in the space dedicated to this chapter, but it suffices to say that chartering the unexplored TeV-verse was well-motivated, not only from a dark matter perspective but also due to other theoretical (e.g. electroweak naturalness, matter–antimatter asymmetry, strong *CP*-problem) and experimental (e.g. anomalous magnetic moment of the muon, neutrino masses in the eV range) puzzles.

In contrast, the main physics goal of LHCb is to explore what is known in jargon as *flavor physics*, although in all honesty, it should be called *quark flavor physics*. In the energy range between 2 and 10 GeV approximately, the quarks do not show

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up as free particles, but instead, they form bound states, analogous to how protons, neutrons, and electrons appear to us as atoms or molecules. These bound states are held together by the strong force, and the theory describing this force is known as *quantum chromodynamics* or *QCD*.

Due to historical reasons, physicists let their imagination fly and named new quantum numbers based on the human senses, so the quarks have *flavor* (u, d, c, s, t, b) and *color* (red, blue, green), besides other known properties such as electric charge or spin.[1] QCD is a very peculiar force if we try to compare it with the more familiar effects of gravity or electromagnetism. If we consider two masses, the gravitational interaction between them *decreases* if we pull them apart, and *increases* if we move them closer to each other. In QCD instead, the opposite happens: when quarks and gluons are *next to each other* (let us simply say *very close*) they do not exert a force, but when we try to pull them apart there would be a strong force that will put them back together to the same *very close* configuration. This phenomena goes under the name of *asymptotic freedom*, and it is such an important phenomena that their discoverers David J. Gross, H. David Politzer, and Frank Wilczek were awarded the Nobel Prize of Physics in 2004. Hence, when quarks come together at energies in the 2–10 GeV range,[2] the strong force binds them in what we call *hadrons*, that can be classified as *baryons* (bound states of three quarks, the most famous for us being the proton and neutron) or *mesons* (bound states of a quark and antiquark pair, here we find the pions and kaons, for instance). Indeed, there is a large number of such bound states, and flavor physics studies the different transition processes that occur during the *hadron* decays.

The LHCb experiment has been originally designed to study in detail the decays of B mesons (which are bound states of a b quark and an anti-b quark copiously produced at proton-proton collisions) and other hadrons containing b or c quarks, while measuring properties (masses, lifetimes, branching ratios, and other observables) of the different hadrons. To accomplish this goal, LHCb requires an exquisite precision to measure the momenta and lifetimes of these particles at *low energies*. Since the LHC collisions do generate an enormous amount of particles with *low momenta* (see Fig. 1), the LHCb experiment must have a different strategy than that of ATLAS and CMS.

Instead, LHCb (i) is a *single-arm* detector instrumented in the forward region (covering an angle between 10 and 300 mrad), which allows to fully characterize the decay products of B mesons and other heavy flavor hadrons (see Fig. 2), (ii) has the ability to reconstruct decay vertices with a very high spatial resolution (this is, separated by very small distances (of the order of several μm), (iii) is capable of a very precise particle identification that allows to identify individual hadrons such as kaons and pions, and (iv) can measure momenta at a lower threshold than ATLAS and CMS. On top of this, and to allow the detector to cope with such a high number of

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[1] Lucky for us, no new quantum numbers have emerged, or we would be speaking of the odor and sound of quarks.

[2] The upper range corresponds to roughly twice the b quark mass. The top quark, having a mass of about 175 GeV, does not hadronize, and we will not be concerned about it in what follows.

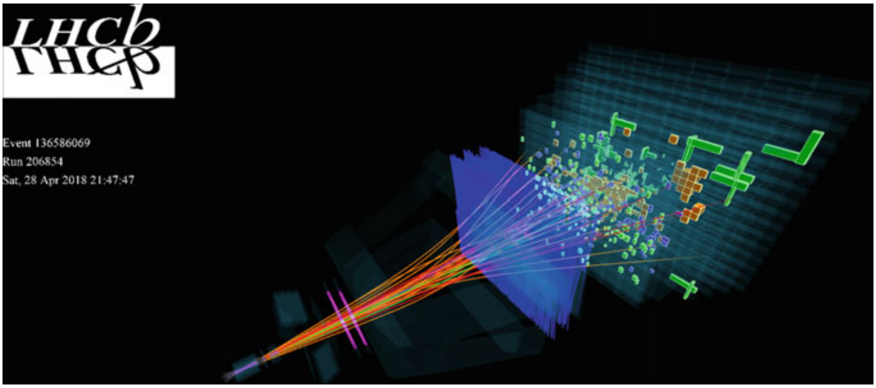

Fig. 1 Typical event display of a heavy flavor process recorded by the LHCb experiment during 2018. The different sub-detector stations (tracking systems, calorimeters, and vertex locator) are shown, as well as the tracks and calorimeter deposits. Different types of particles have different colors associated **(LHCb/CERN)**

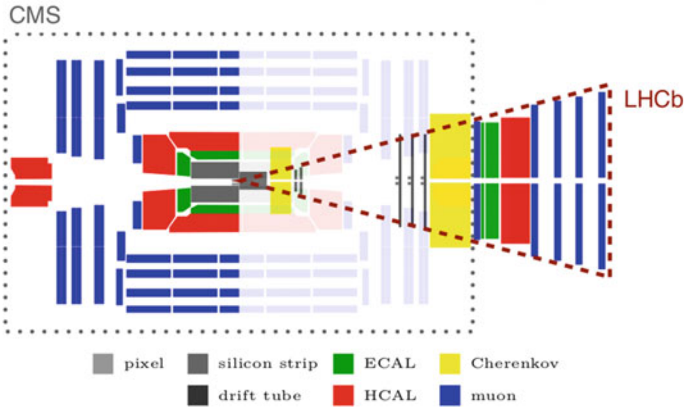

Fig. 2 Schematics of the LHCb and CMS detectors one of top of the other, showing the different coverage regions between the two experiments **(CMS/LHCb/CERN)**

particles at the *low energy regime*, the LHC delivers fewer proton-proton collisions to LHCb than to ATLAS and CMS, leading to a smaller fraction of recorded data (approximately 5–10%) [1].

This *quality data* is optimally selected to fully exploit the flavor physics program but is certainly a price to pay in comparison to ATLAS and CMS when searching for *needle in a haystack* type of rare events.

How can then the BSM program of LHCb rival that from ATLAS and CMS? Well, precisely exploiting the LHCb features that flavor physics requires. For example, needing to identify the flavor of the decay products, having to deal with particles with low momenta, normally arising from the decay of *new neutral particles* with masses in the 1–100 GeV[3] range or particles that are able to fly a macroscopic appreciable distance before decaying, would become really challenging at ATLAS and CMS (either due to their design or because of the optimization of the reconstruction algorithms). Concrete examples for each of these cases have been collected in the "Unleashing the full power of LHCb to probe Stealth New Physics" Stealth White Paper [2], where the *stealthiness* of the *new physics* is with respect to the GPDs.

In the rest of this chapter, we will then describe a selection of LHCb searches that target several dark matter scenarios that often feature more than one particle, hence we will refer to those as *dark sectors*. These dark sectors would contain one dark matter particle candidate that would be stable, colorless, and electrically neutral, but we will not impose the condition of satisfying the relic density. In other words, these dark sectors correspond to the approach of simplified models detailed in previous introductory chapters. We will hunt for both the dark matter particle itself and also for *mediators*: particles that connect the visible sector (where the Standard Model particles live) with the dark sector, where the dark matter particle resides (in jargon particle physicists also talk about *portals* to the dark sector).

2 On the Hunt for Dark and Light

LHCb has searched for a low mass particle, either *prompt* (decaying within a negligible distance from the proton-proton collision) or *displaced* (flying a certain distance before decaying), and decaying into two muons [3] (see Fig. 3). This low mass particle is studied here in the context of a *dark photon*, a new vector boson (like the photon or the Z-boson) that has a small mixing with the SM photon via a mechanism known as *kinetic mixing* (ε). Leaving technical details aside, this kinetic mixing yields suppressed couplings to the SM particles (due to a myriad of experimental constraints which we display later in Fig. 4), but at the same time, this *dark photon* can act as a portal to the dark sector. The search carried out at LHCb is similar to those performed by ATLAS and CMS (described in previous chapters), which also hunt for this dark photon decaying into a pair of muons of opposite charge, since the dark photon is electrically neutral. In spite of the similar final state, we note that ATLAS and CMS consider instead a different production mechanism (since they study a different dark sector), and hence a one-to-one comparison can not be established. LHCb provides competitive limits in the 1–30 GeV range for the prompt case and world-leading limits for the displaced case down to 214 MeV (di-muon threshold). The latter result could be extended if the analysis considered electrons instead of muons. However, this final state entails additional complications and is being scrutinized by the collaboration.

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[3] We will dub this mass interval as *light* or *low mass*, in contrast with ATLAS and CMS that in addition can hunt for particles with masses above 100 GeV and up to few TeV. We stress that both ATLAS and CMS can also hunt for particles in the light regime, but with a few exceptions (muon final states) it is notoriously challenging.

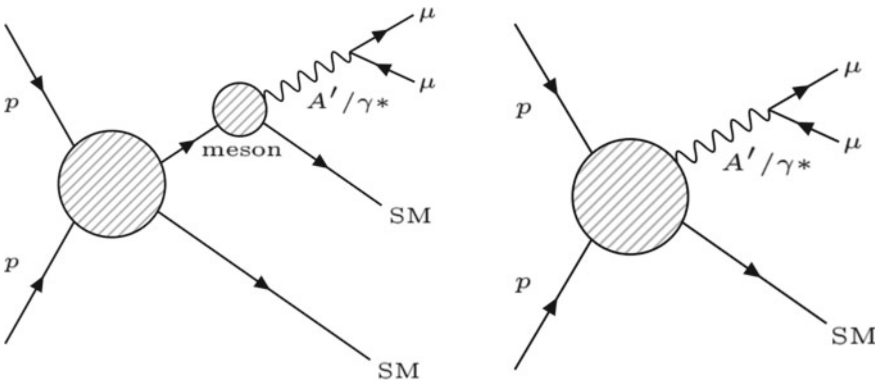

Fig. 3 Production and decay mechanisms of the dark photon (A') described in the text. There are two possible production mechanisms: from a meson decay (left) or directly from proton-proton collisions (right)

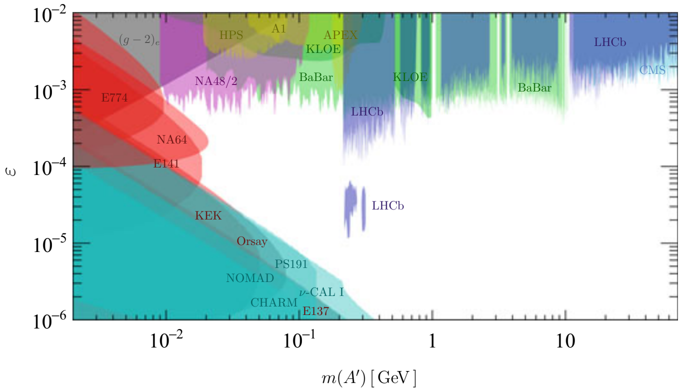

Fig. 4 Comparison of the results to existing constraints from previous experiments **(LHCb/CERN)**

A large dataset collected by the detector from 2016 to 2018 is used, consisting of events containing at least a pair of muons with certain loose requirements on their kinematics. This first step of the selection happens *online*, this is, immediately after data collection from the LHC proton-proton collisions, thanks to the fast LHCb *trigger* system.

Then, pairs of muons are combined to form photon candidates. A more stringent selection consisting of kinematic and particle identification requirements are applied on these candidates, which are also required to form a decay vertex of good quality. This is done to remove candidates that are produced from known processes other than the process of interest, and are known as *background components*. These may consist of muons produced from the decay of heavy-flavor particles, or kaons and pions misidentified as muons by the particle identification system, among others.

One of the most challenging background components in the case of the search for a displaced dark photon are the material interactions with what is known as the radio-frequency foil of the *vertex locator*, or VELO. This envelope, consisting of an aluminum alloy, surrounds the VELO and serves as a physical separation with respect to the LHC beam pipe, suppressing any potential heating or electrical interference on the very delicate silicon sensors of the vertex locator, among others. However, particles from the proton-proton collisions may interact with the foil, leading to the presence of decay vertices that would look like potential candidates of interest. This background component is efficiently suppressed thanks to the use of a very precise mapping of the foil and becomes one of the dominant background components for most of the searches of displaced particles directly produced from proton-proton collisions. In layman terms, we are simply performing an *X-ray* of the LHCb detector!

In the search of *prompt* dark photons, only candidates with masses from 214 MeV to 70 GeV are used. The lower limit corresponds to twice the value of the mass of the muon, which is the lowest possible mass of a particle decaying into a pair of muons. The choice of the upper limit is driven by the fact that the number of events satisfying the selection decreases dramatically after this value, being the available data not enough to perform a precise study. For the case of *displaced* dark photons, an even smaller region of mass candidates is explored, from 214 to 350 MeV, where the upper limit is chosen due to similar efficiency reasons as that for the *prompt* search.

Finally, differences in the selected data with respect to Standard Model predictions are computed, where an excess in these differences would be a hint of the existence of a *new physics* particle. No excess has been found, and a large region of mass and displacement of a hypothetical dark photon has been excluded, as shown in Fig. 4.

Together with this *dark photon* model, other potential scenarios that include the presence of a prompt or displaced particle decaying into two muons have been considered [4]. Scenarios that (a) consider the decay of a *dark hadron* into two muons (where the *dark hadron* is part of a *dark sector*), (b) where the production of this new particle would involve the presence of new Higgs bosons, or (c) where the pair of muons is accompanied by one or two b quarks that hadronize in several final states[4] have been studied, among others. No excess has been found for any of these different scenarios.

3 Dark Sectors, Quarks, and *Jets*

Another interesting signature to look for would consist of a low mass particle decaying into two *quarks*, instead of into two *muons*. The search strategy would be significantly different depending on the quark flavor since *light quarks* (u, d, s) would hadronize in kaons and pions, and *heavy quarks* (c, b) would hadronize in heavy flavor D and B mesons.

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[4] Motivated by an existing result [5] from the CMS collaboration.

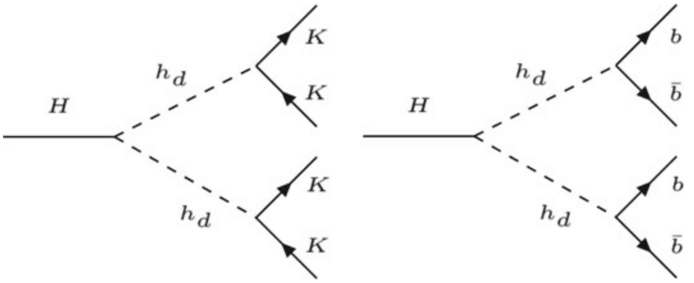

Fig. 5 Schematic of production of two dark hadrons into a pair of quark and an anti-quark, and produced from the decay of a Higgs boson. On the left, the dark hadron decays into light quarks that then hadronize into kaons, while on the right the dark hadron decays into b quarks

Light hadrons such as kaons and pions do not decay within the detector and can be easily reconstructed with high efficiency as *one track per hadron* thanks to the tracking and particle identification systems. A potential search involving a *displaced* low mass particle decaying into pairs of kaons has been proposed [6]. Here, this new particle would be produced in pairs from the decay of a Higgs boson, and then decay into two kaons (see Fig. 5). Using only simulated data, a suitable strategy, as well as projections on the potential exclusion of this search, are studied, showing the capabilities of LHCb to provide competitive results for this kind of signature. Although still not complete, the collaboration is preparing an analysis in this regard towards a publication in the near future.

On the other hand, B and D mesons are *unstable* particles that decay within the detector, either into other unstable particles (that also decay) and/or into stable particles. This leads to a situation where a large number of decay vertices have to be reconstructed to characterize a single heavy flavor quark, having an impact on the reconstruction efficiency. To achieve a reasonable reconstruction efficiency, the so-called *jet reconstruction technique* is used instead, making use of all the particle tracks produced from the decay vertex of the quark without having to reconstruct all the decay vertices.

LHCb has searched for a hypothetical *dark hadron* decaying into *two heavy flavor quarks,* produced in pairs from the decay of a Higgs boson [7], as sketched in Fig. 5. First, the dataset collected between 2011 and 2012 is filtered by requiring events to have a *displaced vertex* with a minimum number of associated tracks. This helps to remove most of the *background contributions*, including those from *material interactions* as previously described. Then, the jet reconstruction technique is used to reconstruct jets from heavy-flavor quarks, and pairs of jets are combined to obtain the dark hadron candidates. Only *displaced* candidates with masses between 25 and 50 GeV are considered, due to efficiency reasons. A similar but not the same technique to that of the search for a *dark photon* is finally used, in order to search for any potential excess: a complementary region of masses and lifetimes to those studied by ATLAS and CMS is studied, and no excess has been found as shown in Fig. 6.

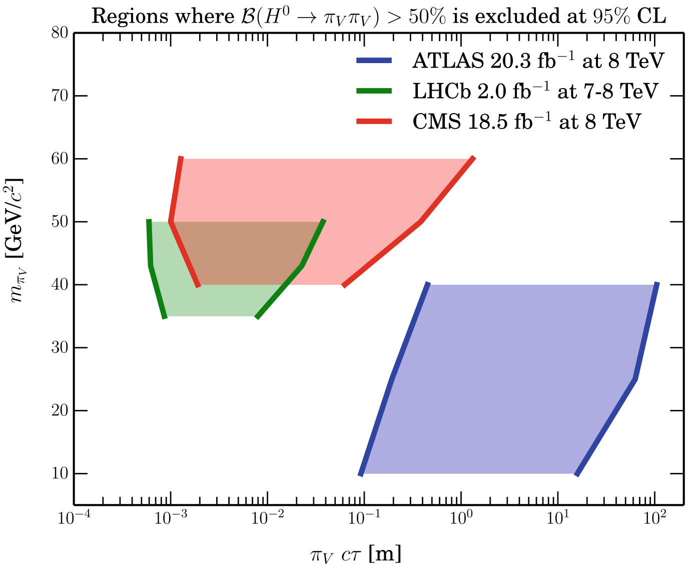

Fig. 6 Comparison of the results to some of the existing constraints from other experiments **(LHCb/CERN)**

4 Matter, Antimatter and Dark Matter

Finally, a very interesting model that attempts to both explain the matter–antimatter asymmetry in the Universe and the existence of dark matter, has been recently proposed [8]. The mechanism behind this model, known as *B-mesogenesis*, postulates a dark matter candidate produced from the decay of a B meson (among other particles containing a b quark), together with other ordinary particles detectable at a collider experiment (see Fig. 7). Because of its unique design (due to the physics

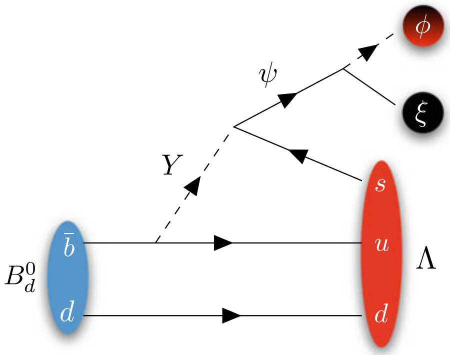

Fig. 7 Example of the decay of a B meson into a Λ baryon (detectable), and a dark matter candidate ψ which remains invisible to the detector [8]

goals of studying flavor), the LHCb detector becomes a natural candidate to search for this kind of signature.

The capabilities of LHCb to test this model have been discussed in [9], where a search strategy was proposed and potential exclusion limits were obtained using simulated data. One of the main differences of this search with respect to those previously described in this section is the fact that the hypothetical *dark matter* particle, invisible and hence not reconstructable, would be produced from the decay of *another unstable particle*, and not directly from proton-proton collisions: constraints on the displacement of the mass and decay vertex of the parent particle (a B meson) are extremely helpful and can be exploited as part of the selection strategy. Then, the rest of the strategy would consist of reconstructing the accompanying products of the decay of the B meson. With all these ingredients and in a similar way as ATLAS and CMS do, an excess on the distribution of *missing energy* can be measured, which would correspond to that of the invisible dark matter particle.

The exclusion potential from this study shows very encouraging prospects towards a future search at LHCb, which is already ongoing and to be completed in the near future.

5 Contributing to the Hunt for Dark Matter

In brief, the LHCb detector, originally conceived to explore the intricate hadronic world, can exploit its design capabilities to hunt for dark sectors with (a) particles in the 1–100 GeV range decaying either prompt or long-lived, (b) decay products with low transverse momentum and (c) dark particles stemming directly from B-meson decays. These are just a sample of an expanding physics program at LHCb and one can expect more searches in the near future, probing previously uncharted dark lands.

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