Snowmass2021 - Letter of Interest

Studies of dark shower benchmarks

Thematic Areas: (check all that apply □/■)

■ (EF9) BSM explorations
■ (EF10) Dark Matter at colliders
■ (TF7) Collider phenomenology

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Abstract:

The search for dark matter in the past century has led to a variety of theory models that need to be explored in an unbiased way in order to make concrete progress in understanding dark matter. With this in mind, we propose a systematic survey of a class of dark sector models known as dark QCD models. In these models, dark matter is a composite object arising from confinement in a non-abelian sector where its constituent dark quarks are situated. Concentrating purely on the hadronic final states emerging in such models, we will demonstrate the validity of the underlying Monte Carlo tools, set up analysis machinery, and investigate a set of benchmarks that can be studied in more detail by the experimental collaborations.

With dark matter (DM) composing about 25% of the Universe, understanding its origin and fundamental properties remains one of the pressing issues of 21st century particle physics. Despite enormous experimental and theoretical progress, the widely hunted Weakly Interacting Massive Particle (WIMP) DM remains elusive. These two observations together necessitate exploration of dark matter models beyond WIMPs. Recent phenomenology papers [1–5] have explored the possibility of accessing the dark sector in non-WIMP scenarios with unique collider topologies. A class of theoretical models featuring dark matter candidate particles include a hidden portal particle, with much weaker interactions with SM particles, and a complex dark sector [6].

Hidden valley models with a new SU(N_{dark}), also termed *dark QCD* models for their similarity to SM QCD, predict fundamental components (dark quarks, q_{dark}) that are confined at an energy scale comparable to that of QCD [7]. These models can lead to signatures of highly collimated particles, resembling hadronic jets that include dark sector particles and their decay products (*dark jets* from dark showers [8]).

Concrete models of DM that realize one or more dark QCD symmetries include for example asymmetric DM [9], electroweak SUSY in extended models containing a dark sector [10], self-interacting DM [11], and strongly-interacting DM [12]. The large number of parameters and particles, and their subsequent variety of experimental signals, has led the experimental community to conduct signature-driven searches for these models, instead of searches that target a specific theory.

In this LOI, we consider a subset of signatures of dark jets, with the underlying commonality of including a sizable hadronic component [a]. Dark jets can be broadly characterised by the following features:

1. Dark jets can appear in the detector at different distances with respect to the interaction point. *Emerging jets* contain dark sector constituents that decay back into SM particles, with a signature of many different vertices within the jet area as well as displaced tracks [2,13]. *Displaced jets* arise when long-lived neutral particles produce a dark shower [14–16], and strongly interacting massive particles can interact with the detector material in a way similar to neutrons, leaving no tracks in the inner detector and a jet-like signature in the calorimeters (*trackless jets*) [17,18]. [b]. Prompt dark jets can still be distinguished from SM jets because of their different fragmentation [1].
2. The dark jet may be constituted by a sizable fraction of invisible particles, e.g. stable dark sector particles and DM candidates, and appear as a *semi-visible dark jet*. In this case, one assumes that the lightest particles in the dark sector are the DM candidates [1,3,12,19,20]. For models with a very large invisible fraction and/or a very large displacement, the signature will be that of the so-called *missing transverse momentum (MET)+X* searches, where a visible QCD jet coming from initial-state radiation is accompanied by a large amount of missing transverse momentum.

The sketch in Fig. 1 places these experimental signatures of dark jets according to the invisible and prompt particle fraction in the dark jet.

It is clear that there are connections between these different signatures and models, also as the boundaries between them are not strictly defined but rather one signature merges into another. A further common denominator for many of these benchmarks in LHC searches is the use of the Pythia "Hidden Valley" module [21]. Different values for Pythia parameters lead to the realization of different models and signatures, making it possible to study the connections between them by varying these common parameters.

We propose to review and compare the characteristics of these models in generator-level studies, and further our understanding of the connections between the models and signatures in Fig. 1. As a consequence,

[a] We do not plan to include soft unclustered energy patterns (SUEP) or lepton-jets in our studies, but we will still consider their connections, as these signatures can originate from the same class of models

[b] This is not meant to be an exhaustive list of dark shower models and signatures, and we will be happy to work in synergy with the Theory Frontier for further extensions of this classification

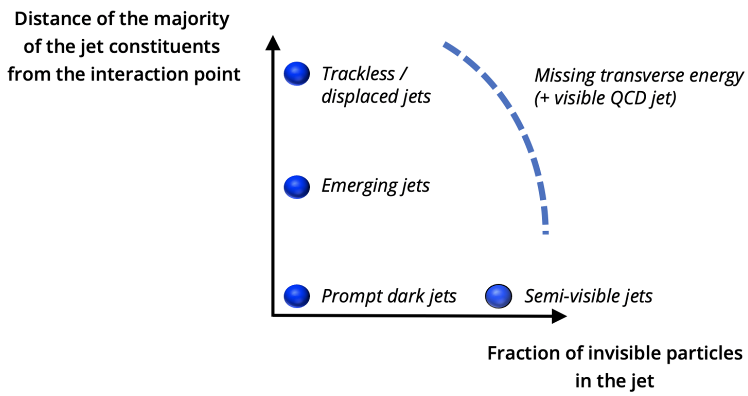

Figure 1: Sketches of search signatures considered in this LOI.

we will contribute to harmonizing and generalizing this subset of models for future studies.

Concretely, we will take the following steps:

- share and document knowledge on the generation of current LHC benchmarks, in terms of parameters of the Pythia Hidden Valley module and of MadGraph models;
- understand the kinematics of the dark jets and associated particles in the different models and signatures by varying the Pythia model parameters;
- understand possible extensions and shortcomings of the models used, in reference to signatures and inclusion in concrete dark matter models;
- publish the generator-level analyses (e.g. Rivet[22]) that we will use for the above studies on GitHub and Zenodo, so that they can also be used to test and validate extensions of these models in Pythia;
- contribute to the discussion of dark shower benchmark models for current and future colliders.
- identify observables sensitive to dark shower, extending on existing studies[23].
- demonstrate reach and shortcomings of existing searches sketched in Fig. 1 for dark sector models under consideration.

The work will take place over the course of the Snowmass 2021 process, mostly within undergraduate and PhD theses. We intend to work in synergy with the LHC Long Lived Particle community and Working Group, following up on the white paper[8], with the LHC Dark Matter Working Group, and within the EF09 and EF10 groups.

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