Popular Science Abstract

Beyond the Standard Model physics is an extensive field that attempts to provide answers to fundamental questions that cannot be found within the Standard Model. The Standard Model is the most complete description of the fundamental particles and forces of the Universe that we have to date. It explains a vast amount of phenomena that we have observed and agrees with data across a large energy scale range [1]. However, the Standard Model still leaves several fundamental questions unanswered and observed phenomena unexplained. One of the main questions is that of *dark matter*. We know that it exists from observing its gravitational interactions, and we know that it is approximately 5 times more abundant than ordinary matter, i.e. matter that we can explain with the Standard Model [2], but we don't know what dark matter is made of.

The motivation behind many Beyond the Standard Model theories is to provide a *dark matter candidate*, i.e. a new particle or phenomenon that can account for the dark matter abundance. Some of the most popular dark matter theories only require the introduction of a single new kind of particle [3], such as the popular WIMP candidate (Weakly Interacting Massive Particle) which appears in several different theories, or the sterile neutrino which are similar to our Standard Model neutrinos but are completely invisible to our detectors. However, there is no reason why the real explanation behind dark matter can't be more complicated than so. In fact, there could be a whole sector of new dark particles, and perhaps even dark forces, that we have not observed yet.

Figure 1: What if there is a whole sector of dark particles? The colored blocks on the left page signify the particles of the Standard Model, the "building blocks" of what we know of the Universe. The dark page on the right suggests that there could be an array of new particles that we haven't found yet.

One such *dark sector* theory is the strongly-interacting dark sector. It is named so because the interactions of the dark particles are similar to the strong interactions of quarks in the Standard Model. Quarks are the particles that make up *hadrons* like the proton and neutron, and the strong force is responsible for keeping the quarks together. The strong force is special in that the interaction between two quarks grows stronger as the two quarks move apart [4]. Imagine the quarks as the two ends of an elastic ribbon; when you pull at the ends in opposite directions the ribbon becomes tighter and the further you pull them apart, the more energy is stored in the ribbon (this can easily be tested by letting go of one end of the ribbon at different distances and feeling the effect). At one point, the energy stored between the two quarks is so high that it is energetically favorable to create a new pair of quarks rather than keeping the original two connected. This can be imagined as cutting the ribbon in half so there are two pieces of ribbon, each with two ends or two quarks. This process creates new hadrons from energy and is called *hadronization* [5]. If there is enough energy in the system the process can go on for a while and essentially create a *shower* of new hadrons. Such high energies are achieved at particle collision experiments at colliders such as the Large Hadron Collider (LHC) at CERN [5]. If there exists dark particles that interact strongly, then they may also hadronize in a *dark shower*. Furthermore, if we can create dark particles in particle collisions, dark showers could happen right under our noses at e.g. the LHC.

Is it realistic to think we could create dark particles at collider experiments? That depends entirely on the theory, so we can choose to consider theories that allow for the creation of dark particles. In the case of the strongly-interacting dark sector, we can introduce a new particle that can be created by Standard Model particles in a collision and subsequently decay to dark particles [6, 7]. Furthermore, the reverse may happen afterwards and some dark particles may decay back to Standard Model particles. This type of dark shower, called the semi-visible dark shower, is particularly interesting, because the dark shower will not be entirely invisible and it leads to phenomenology that we may indeed be able to observe.

This small branch of Beyond the Standard Model theories has achieved more attention in recent years [7, 8, 9, 10], and a dedicated search for such particles within experimental data was conducted for the first time in 2021 by the CMS collaboration [11]. Semi-visible dark showers at collider experiments is the subject of this thesis. The focus is on the kinematics of various dark shower models, including the model used in the CMS search. Additionally, this thesis strives to motivate a discussion of how we handle dark shower model parameters and how we can quantify the visibility or invisibility of a dark shower.

References

[1] Butterworth, J. The standard model: How far can it go and how can we tell? **374**, 20150260. URL http://arxiv.org/abs/1601.02759. 1601.02759.

[2] Planck Collaboration. Planck 2018 results. VI. cosmological parameters **641**, A6. URL http://arxiv.org/abs/1807.06209. 1807.06209[astro-ph].

[3] Peter, A. H. G. Dark matter: A brief review URL http://arxiv.org/abs/1201.3942. 1201.3942.

[4] Altarelli, G. & Wells, J. QCD: The theory of strong interactions. In Altarelli, G. & Wells, J. (eds.) *Collider Physics within the Standard Model: A Primer*, Lecture Notes in Physics, 27–96 (Springer International Publishing). URL https://doi.org/10.1007/978-3-319-51920-3_2.

[5] 9. Quantum Chromodynamics URL https://pdg.lbl.gov/2017/reviews/rpp2017-rev-qcd.pdf.

[6] Han, T., Si, Z., Zurek, K. M. & Strassler, M. J. Phenomenology of hidden valleys at hadron colliders **2008**, 008–008. URL http://arxiv.org/abs/0712.2041. 0712.2041[hep-ph].

[7] Knapen, S., Shelton, J. & Xu, D. Perturbative benchmark models for a dark shower search program **103**, 115013. URL http://arxiv.org/abs/2103.01238. 2103.01238.

[8] Cohen, T., Lisanti, M. & Lou, H. K. Semi-visible jets: Dark matter undercover at the LHC **115**, 171804. URL http://arxiv.org/abs/1503.00009. 1503.00009.

[9] Bernreuther, E., Kahlhoefer, F., Krämer, M. & Tunney, P. Strongly interacting dark sectors in the early universe and at the LHC through a simplified portal URL http://arxiv.org/abs/1907.04346. 1907.04346.

[10] Doglioni, C., Hemme, N., Kulkarni, S. *et al.* Theory, phenomenology, and experimental avenues for dark showers: a snowmass 2021 report URL http://arxiv.org/abs/2203.09503. 2203.09503.

[11] CMS Collaboration. Search for resonant production of strongly-coupled dark matter in proton-proton collisions at 13 TeV. URL https://cds.cern.ch/record/2778946. Number: CMS-PAS-EXO-19-020.