Search for resonant production of strongly-coupled dark matter in proton-proton collisions

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Abstract. A collider search for semi-visible jet final state arising from dark matter, using Run 2 data recorded with the ATLAS detector at the CERN LHC with a center-of-mass energy of 13 TeV is presented. For this search the hidden sector is hypothesized to couple to the standard model via a heavy leptophobic Z' mediator. Semi-visible jets are an unusual final state, where the visible states in the shower are standard model hadrons and the strongly coupled hidden sector contains dark quarks which result in dark hadrons. This gives a final state consisting of a jet aligned with missing energy due a mixture of stable, invisible dark hadrons and visible hadrons from an unstable subset of dark hadrons that promptly decay to SM particles. The resonant production and decay of such a mediator will result in a dijet system of semi-visible jets, leading to missing energy aligned with one of the jets, a signature ignored by most dark matter searches.

1. Introduction

The study of particle physics is focused on our understanding of elementary particles and the means in which they interact. The Standard Model of particle physics (SM) describes the fundamental particles and their interactions, and has so far been highly consistent with experimental data. This sophisticated model gives a complex explanation of 17 fundamental particles in nature, from the vector (g, γ, W, Z) and scalar (H) Bosons to the three generation Fermions (quarks and leptons) [1]. Despite this the Standard Model is incomplete as it does not give a truly sufficient description of the universe. As such, it would not be unreasonable to suspect the existence of new physics at the energy scales explored at the Large Hadron Collider (LHC).

One enduring question we have long been faced with is dark matter, it is well known that dark matter is an obscure and mysterious highly gravitational substance whose evidence is undeniable. Dark matter does not interact with normal matter yet the mere existence of galaxies and the occurrence of gravitational lensing, its presence is indisputable. Dating back to the 1930's there have been theories postulating the existence of dark matter, expressing the curiosity of an unknown form of non-baryonic matter influencing the structure of the universe. Over decades of questioning and observing there has been indirect evidence through astrophysical and cosmological studies such as those of the cosmic microwave background (CMB) [2].

Over time there has been an growing interest in dark matter and and recent years have seen an increase in searches exploring the dark sector, yet there is still to be direct evidence of dark matter. There is no suitable particle in the standard model which fits the role of dark matter and making up 27% of the universe, making the exploration of dark matter a necessity in furthering our understanding of physics. In general most dark matter searches at the Large Hadron Collider (LHC) are focused on Weakly Interacting Massive Particles (WIMPs). Since standard searches as of yet have yield no substantial results, there are a number of phenomenological papers exploring the possibility of approaching the dark sector through unique collider topologies.

1.1. Dark Matter

In the past decade the search for dark matter particles has become a major focus at the LHC, however there has still been no sign of these particles as of yet. The absence of results so far, may mean that if dark matter interacts with SM particles the interactions may be very weak and so the experimental signals are subtle. Combining this with the emergence of new dark matter models which mirror interactions of ordinary matter but have not yet been caught by existing models, may indicate a large class of non-standard dark matter signals may have been overlooked. There are several theories on the nature of dark matter which has led to many different and search and detection methods for dark matter.

1.1.1. Particle Candidates Until the 1980's neutrinos where thought of as potential dark matter candidates, however this theory was abandoned when there was experimental evidence that neutrinos had small but not negligible masses and the potential to form superclusters which would then resolve to galaxies, which is against what is observed in nature. WIMPS (weakly interacting massive particles) are one potential candidate for cold dark matter, this is dark matter which is stable and long-lived enough to initially form galaxies then superclusters. WIMPS evolved from SUSY (supersymmetry) which is an extension of the standard model where there is an additional symmetry between fermions and bosons [3].

1.1.2. Direct Detection There are several direct dark matter detection efforts such as, CRESST-II, XENON10/XENON100 and DAMA/LIBRA. Where these experiments are searching for dark matter in sub MeV scale scattering events [4]. The focus is to attempt to record an event when a dark matter particle is scattered off of a target material, however these events are very rare. The central focus of this experiment comes from the idea that in the early universe dark matter was produced thermally and declined through annihilation to ordinary matter reaching stability. Direct detection methods are searching for dark matter signal excess over the background, however there have been no promising results as yet.

1.1.3. Collider Searches Searching for dark matter in accelerators is a far more arduous task. In order to come up with collider testable scenarios it requires a combined effort of theorists and experimentalists. Naturally dark matter is not luminous and so in collider final states one would expect a lot of missing energy (MET) otherwise referred to as missing transverse momentum (p_T)

Missing energy in an event is essentially energy which has not been detected but must be there due to conservation of energy and momentum. The initial particles (usually protons) move along the beam axis and so the total p_T of all the particles must be zero. The missing (transverse) energy accounts for undetected energy in order for this conservation to be obtained and is defined as the negative of sum of scalar p_T of all the objects, termed as MET.

One search technique for dark matter involving a missing energy signature is guided by simplified models including a WIMP-like dark-matter particle and a mediator particle which would be able to interact with the known ordinary matter. This mediator particle may be a known particle or unknown, hypothetical particle. These types are searches can be useful as they may be simple in general but can be used as benchmarks between LHC results and those from non-collider dark matter experiments. Another search method from simplified models is when the mediator is a hypothetical particle, instead of searching for the dark matter particle, search instead for the mediator through its decay into SM particles [6].

In addition to missing momentum from dark matter candidate particles, in general searches try look for at least one highly energetic object such as a jet or a photon. In the detector quarks which have colour charge can split into gluons which in turn can decay into quark-antiquark pairs leading to a cascade of particle similar to that of photons. This collection of quarks and gluons (referred to as partons) leads to colour neutral hadrons which are then detected by depositing energy on the detectors, the collection of these collimated bunches of hadrons are referred to as jets, where essentially each jet is coming from a single parton [5].

Our focus will be designing an analysis strategy for a non-standard dark matter signal search through unique collider topologies. Recent phenomenological papers have explored the possibility of accessing the dark sector with unique collider signatures which have never been considered. The base for the proposed study will be jets linked to the dark sector. The following sections discuss the study and search approach, section 3 discusses the model for a unique collider signature search. Section 4 discusses methodology of the analysis strategy and section 5 is the work plan which gives an outline of steps going forward.

2. Semi-Visible Jets

The present research interest in an unusual topology which are jet-like collider objects referred to as semi-visible jets, where the visible states in the shower are Standard Model hadrons and the strongly coupled hidden sector contains dark quarks. These dark quarks the decay and hadronize and decay to stable and unstable quarks. The unstable quarks then decay to SM quarks, giving a final state of a jet aligned with missing energy.

We consider the resonant production process where by two quarks decay to a leptophobic Z' boson mediator giving to dark quarks $q\bar{q} \rightarrow Z' \rightarrow \chi\bar{\chi}$ [7]. The leptophobic Z' boson mediator arises from broken U(1) symmetry, with couplings to SM quarks g_q and dark quarks g_χ. The dark sector contains many flavours of dark quarks $(\chi_1, \chi_2, \chi_3, ...)$ which form bound states referred to as dark hadrons, and these dark hadrons may be stable or unstable.

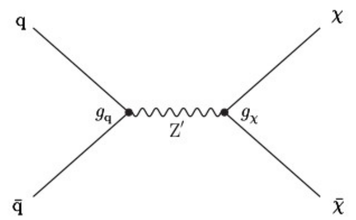

Figure 1: Feynman diagram

The unstable dark hadrons decay promptly to SM quarks, however the stable dark hadrons are the DM candidates and pass the detector without interacting. This leads to a collimated mixture of visible and invisible particles, which are termed as semi-visible jets. Thus, the signature of this model will be a pair of jets where on if the jets is aligned to the missing transverse energy, and the amount of missing transverse energy us expected to be moderate because both of the jets contain visible particles, which means that a portion of the transverse component of the overall MET will cancel out when the jets are produced back to back.

The SM jets arise from a multi-step process, the dark quarks shower and hadronize in the dark sector and, the unstable dark hadrons then decay promptly to SM quarks and then finally the SM quarks shower and hadronize visibly. Since the SN quarks are much less massive than the dark hadrons they are produced in the intermediate decay step with a much higher relative momentum cause the SM particle showers to spread out. Thus the jets are expected to be wider than typical SM jets.

The fraction of stable and unstable invisible dark hadrons, given by $r_{inv} = N_{stable}/N_{total}$ [8], can have a value between 0 and 1 and since events containing jets aligned with missing transverse momentum are explicitly rejected from the signal regions of existing collider DM searches, a large portion of the parameter space of this model has not yet been covered, in particular events with intermediate values of r_{inv}. Current DM searches are more sensitive to dark sector models having an $r_{inv} \approx 1$ yielding events having high missing energy and some initial-state radiation [9] and other current dijet searches favor dark sector models having $r_{inv} \approx 0$ which yield events having two jets but low missing energy [10]. Thus this search supplements these efforts.

3. Analysis Strategy and Signal Selection

In this search from the model the leptophobic Z' boson has a mass of 1500 GeV, the jets are reconstructed using the Anti$_{kt}$10 algorithm and the fraction of stable vs invisible dark hadrons in this case is 0.3. The signal generation is done using MadGraph for the matrix element, and Pythia8 for shower and hadronization using the Hidden valley model as it uses dark sector showering.

For our Signal selection, since our final state is just jets we require a lepton veto of no electrons or muons with transverse momentum $p_T > 7$ GeV as the detector cannot distinguish at low GeV values. The leading jet transverse momentum must be greater than 250 GeV, without this selection there are too many initial-state radiation jets polluting the topology. Since we will have a jet aligned with the MET, we require that the $\Delta\phi$ between the MET and the closest jet must be less than 2, and we require that the number of bjets are less than 2. The signal has two jets produced back to back both containing invisible particles, the semi-visible jet (SVJ) is chosen as the jet closest to the MET.

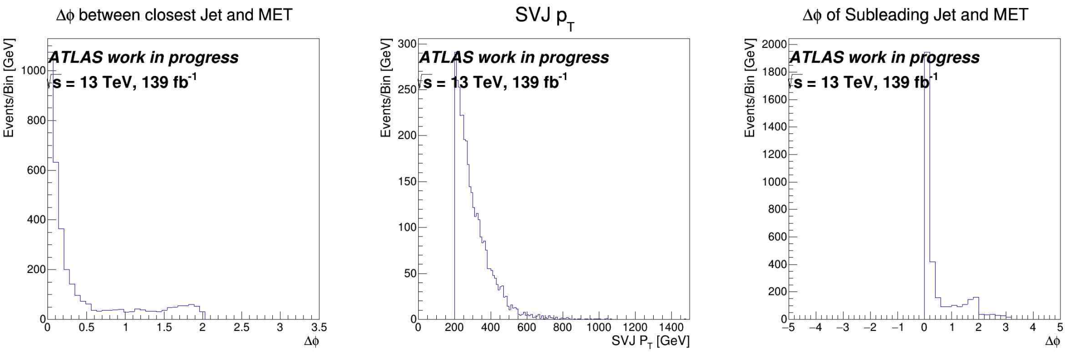

Figure 2: The distribution of the $\Delta\phi$ between the closest jet and MET (left) which selects the SVJ, and the p_T of the SVJ (middle), $\Delta\phi$ between the subleading jet and MET.

It is interesting to note that the it most cases the subleading jet is tagged as the SVJ, as shown in figure 2. The Anti-SVJ is jet produced back to the SVJ which is thus the jet farthest from the MET. Again we see that in most cases the leading jet is tagged as the Anti-SVJ as shown in figure 3.

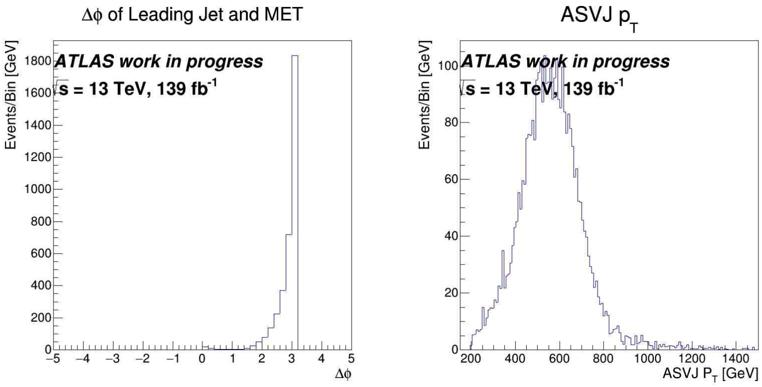

Figure 3: the distribution of the $\Delta\phi$ between the farthest jet and MET (left) which selects the Anti-SVJ, and the p_T of the Anti-SVJ (left).

The largest background contribution is from multijet events, however finding discriminating variables to probe is the greatest challenge as multijet has an almost identical distribution for all variables currently considered.

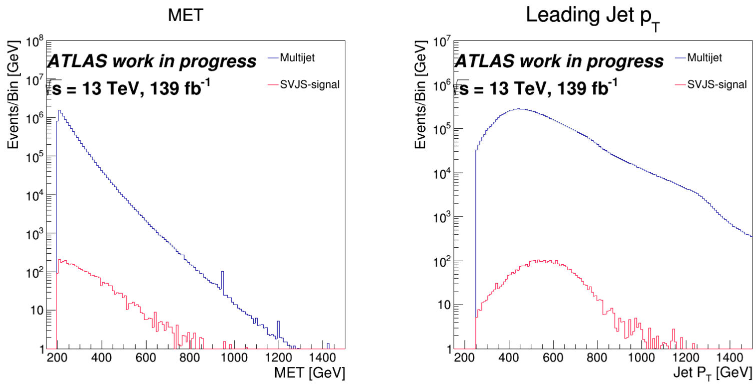

Figure 4: MET for Signal against Multijet (right), Leading jet transverse momentum for Signal against Multijet (left).

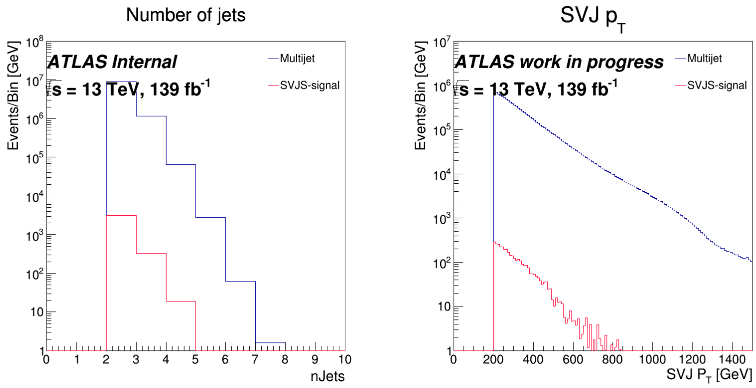

Figure 5: Number of jets for Signal against Multijet (right), SVJ transverse momentum for Signal against Multijet (left).

The goal is to construct the resonant mass peak accounting for the invisible fraction, figure 6 shows the invariant mass of the leading and sub-leading jet mass without accounting for the invisible fraction, where the mass peak is around 800 GeV and not the 1500 GeV mass of the mediator Z' boson.

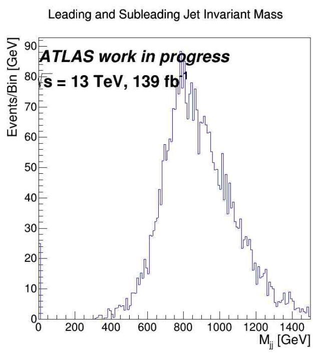

Figure 6: Invariant mass of leading and sub-leading jets

4. Conclusions

A preliminary study of semi-visible jets search in resonant production mode was presented. The distributions describing signal characteristics are shown, with an initial look at largest background. The search is ongoing in ATLAS.

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