Semi-visible Jets: Dark Matter Undercover at the LHC

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It is possible that the dark matter is the remnant of strongly dynamics in a hidden sector (similar to QCD), that connects to us though a weakly coupled portal. The stable hadrons would constitute the dark matter, while unstable hadrons would decay back to the Standard Model. If the fundamental constituents of this sector were produced in collisions at the LHC with transverse momentum much larger than their mass, they would undergo a QCD-like shower yielding a spray of final states that are some combination of dark matter and Standard Model particles. This letter explores the simple possibility that the dark sector states are produced resonantly via a new Z', and that decays back into the Standard Model are leptophobic. The signature would be jets-like objects, made of Standard Model hadrons overlaid with clusters of dark matter. We will demonstrate that this signal would be missed by the current suite of searches employed at the LHC. Then we will provide a simple strategy that can be employed to probe this model, along with a Simplified Model-like parameterization that allows one to organize the possible range of signatures. Expected discovery reach and exclusion limits for the 14 TeV LHC are computed – assuming Standard Model production cross section and a 100% branching ratio into the dark sector, a Z' mass of 4 TeV can be probed using 100 fb^{-1} of data.

The existence of dark matter provides one of the strongest motivations for physics beyond the Standard Model, and its discovery is a focus of the Large Hadron Collider (LHC). Under the assumption that the dark matter particle is neutral and stable, it escapes the detector and manifests as large missing transverse energy ($\not\!\!E_T$). The LHC collaborations have developed a comprehensive search strategy to look for signals with significant $\not\!\!E_T$, accompanied by jets and/or leptons (see [1] for a review). These searches are typically cast in terms of a Simplified Model [2] for supersymmetry or an effective theory of dark matter interactions [3, 4]. However, a class of dark matter signatures exists that evades this entire suite of analyses. Namely, topologies where the dark matter lurks undercover within hadronic jets. The purpose of this Letter is to propose a straightforward discovery strategy for these "semi-visible" jets.

Semi-visible jets could occur if the dark matter is the stable (or meta-stable) remnant of a more complicated dark sector. The dynamics of non-trivial dark sectors have been explored in many contexts—for example, [5–18]. In these models, the dark sector contains a dark matter candidate(s) along with, possibly, new forces and matter fields. Typically, some messenger state exists that couples the dark sector to the Standard Model. If the messenger is accessible at colliders, dark sector states can be produced, which could lead to unique signatures such as large particle multiplicities, displaced vertices, multiple resonances, and lepton jets [19**?** –29].

Another possibility is that the final state may contain a new type of jet object, which we refer to as a semi-visible jet. A semi-visible jet arises, for example, when dark matter is produced through a strongly coupled sector that contains other light degrees of freedom that decay hadronically. **TL: good enough argument?** In this case, dark matter production will always be accompanied by hadrons, resulting in a hadronic jet that is closely aligned with the $\vec{\not\!\!E}_T$ in an event. Most LHC Simplified Model searches that involve $\not\!\!E_T$ require a minimal angular separation between the jets and $\not\!\!E_T$ to remove the QCD background contamination arising from jet-energy mis-measurement []. Such a cut vetoes any event containing semi-visible jet.

To illustrate this point quantitatively, Fig. 1 shows the distribution of $\not\!\!E_T$ and angular separation ($\Delta\phi$) for QCD, as well as an example Simplified Model (the squark-neutralino model) and dark-sector model. The Simplified Model signature is due to squark pair production, decaying to two jets and two dark matter particles. The dark-sector model, which will be described more fully later, is one of the canonical examples of a Hidden Valley model which leads to semi-visible jets. Clearly, both the jets+MET and semi-visible examples produce considerable $\not\!\!E_T$, with tails that extend much farther above the QCD distribution. However, the angular separation of the $\not\!\!E_T$ and the momenta of the three leading jets is much larger for the jets+MET example, compared to the semi-visible jets case. Indeed, the semi-visible example aligns more closely with the expected distribution for the QCD background. Because typical LHC searches require that $\Delta\phi > 0.5$, the semi-visible signal is almost completely removed.

In more details, the standard Hidden Valley scenario we are considering involving a new non-Abelian dark force where the dark-sector is accessed via a new Z' gauge boson [21]. The portal sector of the model is described by the following Lagrangian:

$$\mathcal{L}_{\text{portal}} = -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} - m_{Z'}^2 Z'_\mu Z'^\mu - Z'_\mu \Big(g_{Z'}^{\text{dark}} J^\mu_{\text{dark}} + g_{Z'}^{\text{SM}} J^\mu_{\text{SM}} \Big), \tag{1}$$

where J^μ_{SM} is the SM baryon current and J^μ_{dark} is a con-

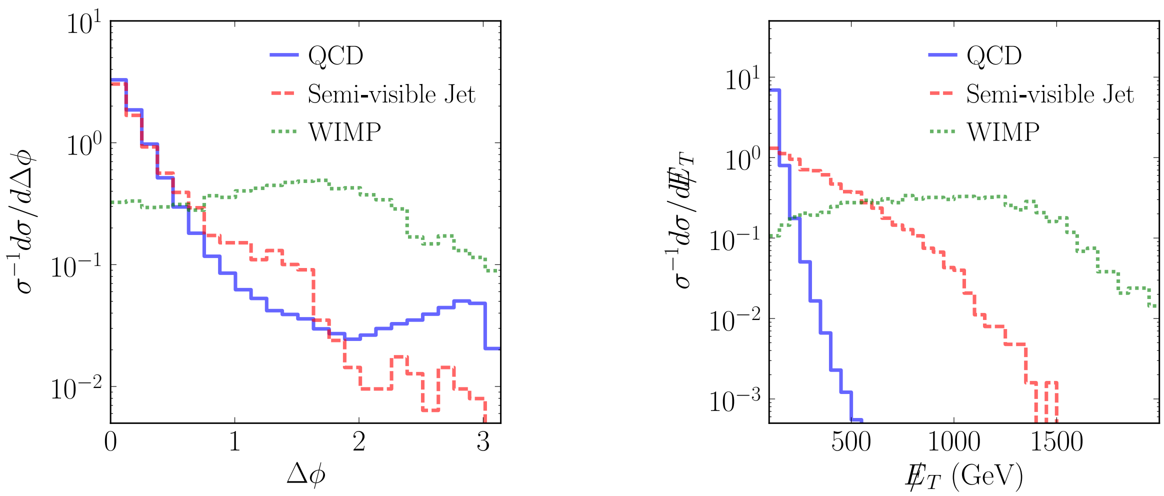

FIG. 1: **On the left, need MET figure.** The minimum $\Delta\phi$ between $\vec{\not{E}}_T$ and the momenta of the three leading jets. Shown in blue is the distribution for QCD background. Shown in red is the distribution for Z' decaying to dark sector $\chi_i^\dagger\chi_i$. Shown in green is a pair of supersymmetry squarks $\tilde{q}$ each decaying into a quark and a neutralino χ_0.

served current in the dark sector. Note that the Z' is treated as a Stueckelberg field – the Higgs sector has been neglected and is not relevant for the LHC phenomenology discussed below. The couplings $g_{Z'}^{\text{dark}}$ and $g_{Z'}^{\text{SM}}$ in Eq. (1) in general do not have to be equal. We will focus on the phenomenologically interesting case where $g_{Z'}^{\text{dark}}$ is reasonably large, such that the Z' will decay into the dark sector sufficiently frequently.

Next the dark sector Lagrangian will be introduced. One way of realizing semi-visible jets is through a "dark shower": the creation of high p_T states charged under a new non-Abelian force would lead to a shower analogous to QCD, whose low energy by products would be a combination of dark matter and Standard Model hadrons. In general, there are many possibilities for a strongly coupled dark sector. However, as we will argue below, the collider signatures of interest are only sensitive to a few gross features of the model. In order to be explicit, we will consider an $SU(2)_{\text{dark}}$ gauge theory with two scalar flavors; changing the number of colors, introducing more flavors, and/or choosing the dark sector matter to be fermions would have no qualitative impact on the observables and would only lead to a change in the choice of simplified parameterization introduced below. The Lagrangian for the dark sector is

$$\mathcal{L}_{\text{dark}} = -\frac{1}{2}\text{tr}\, G_{\mu\nu}^2 + \left|D_\mu\, \chi_i\right|^2 - V\big(\chi_i\big), \qquad (2)$$

where $G_{\mu\nu}$ is the $SU(2)_{\text{dark}}$ field strength, and $\chi_i = \chi_{1,2}$ denotes scalar quark field. V is the potential for the matter fields to be specified later. The χ_i will be produced at the LHC due to the presence of the Z' in the covariant derivative

$$D_\mu\chi_i = \partial_\mu\, \chi_i - i\, g_{Z'}^{\text{dark}}\, Z'_\mu\, Q_{ij}\, \chi_j - i\, g_{\text{dark}}\, G_\mu\chi_i, \qquad (3)$$

where Q_{ij} is the charge matrix. Self-interactions of the χ_i will not be relevant for this study, so we will only consider mass terms in the potential:

$$V\big(\chi_i\big) = m_{ij}^2\, \chi_i^\dagger\, \chi_j + \big(b\, \epsilon_{ij}\, \chi_i\, \chi_j + \text{h.c.}\big), \qquad (4)$$

for the two possible $SU(2)_{\text{dark}}$ contractions. Note that Q_{ij} does not have to commute with the mass matrix m_{ij}^2: some of the mass terms may be forbidden by gauge invariance. **TL: not sure which gauge invariance you're referring to, $SU(2)_{\text{dark}}$ or the broken $U(1)_{Z'}$?, the $U(1)_{Z'}$ breaking masses can be induced by a Higgs**

We will assume that the $SU(2)_{\text{dark}}$ confines at a scale $\Lambda_{\text{dark}} \ll m'_Z$. A QCD-like dark shower will occur when when the mass parameters in V are near or less than the scale of Λ_{dark} so that many dark gluons and scalar quarks may be produced. **TL: small splitting not really necessary? could rely on baryons for small r_{inv}.** The light degrees of freedom are scalar mesons and baryons. Depending on the interactions, some of these dark hadrons can be stable, while the others will decay back to the Standard Model via an off-shell Z'. This is depicted schematically in Fig. **??**. Note that the strength of the dark shower, *i.e.*, how many dark hadrons are emitted and their p_T distributions, is controlled by the size of α_{dark} – this must be included in the simplified parameterization as it impacts the LHC phenomenology. **TL: mention mild effects due to running?**[1]

The detailed spectrum of the dark hadrons in general depend on non-perturbative physics. Nonetheless,

[1] Note that the relationship between the running dark gauge coupling and Λ_d depends on the chosen matter content. We find that the observables of interest are insensitive to these differences, and that one can map between the constraint for a particular α_d to the α_d in another model. We have chosen a **put in specifics** scalar QCD model in order to allow a larger running coupling and neglect spin degrees of freedom.

some properties of the low energy states can be inferred from symmetry arguments. For simplicity, we will neglect higher spin states. Ignoring the Z' coupling and the b-term, the kinetic term preserves an $U(2)_f$ flavor symmetry. Fix a basis where the mass matrix is diagonal, i.e. $m_{ij}^2 = \text{diag}(m_1^2, m_2^2)$; for general unequal masses, only the flavor symmetry $U(1)_1 \times U(1)_2$ remains (**TL: technically there are additional custodial symmetries so the symmetry group is bigger...not sure if we should mention**). It is more more convenient to rewrite the symmetry group as a product of the isospin number $U(1)_{1-2}$ and the baryon number $U(1)_{1+2}$. We can now classify all the light hadrons based on this symmetry. Borrowing intuitions from QCD, we can consider the light hadrons as bound states of fundamental scalar quarks. Table I lists the possible light hadrons and their properties

	Hadrons	$U(1)_{1-2}$	$U(1)_{1+2}$
diagonal meson	$\chi_1^\dagger\chi$, $\chi_2^\dagger\chi_2$	0	0
off-diagonal meson	$\chi_1\chi_2^\dagger$, $\chi_2^\dagger\chi_1$	$+2, -2$	0
baryon	$\chi_1\chi_2$, $\chi_1^\dagger\chi_2^\dagger$	0	$+2, -2$

TABLE I: Dark Hadron Symmetry Properties

If we add back the Z' coupling with a trivial charge matrix $Q_{ij} = \delta_{ij}$, all the diagonal mesons will decay back to SM quarks. All the charged hadrons will remain stable by flavor symmetries. It is easy to reduce the number of stable hadrons by reducing the flavor symmetry. For example, if we add back a non-zero baryon number violating b-term in the potential, the flavor symmetry will be reduced to the isospin $U(1)_{1-2}$: in this case only the off-diagonal meson will be stable. Another possibility is to add off-diagonal terms in Q_{ij} while setting $b = 0$: in this case only the baryons will be stable. Given the numerous possibilities in our simple two-flavor models, we conclude that in a general hidden sector, it is entirely plausible that one or more of the dark hadrons is stable. Note that the dark hadron spectrum we are considering are analogous to those in QCD: in the limit that the weak interactions are turned off, the charged pions will remain stable while the neutral pions can still decay into photons and lepton pairs through QED interactions.

(TC: Do we want a table that summarizes these different scenarios? Just listing who is stable and who is unstable for each case?)

In our two flavor model, a Z' will decay into a high multplicity of dark hadrons, and all the unstable dark hadrons will decay back into Standard Model hadrons: this model will yield semi-visible jets at the LHC. However, given the wide variations in the dark hadron phenomenology, it is crucial to isolate a few effective parameters to facilitate experimental searches. Since it is difficult to reconstruct all the hadrons from their decay products, a detailed knowledge of the hadron masses and decay modes are not so crucial for searches anyway. The most important variable for dark matter searches would be the $\vec{\not{E}}_T$, which is most sensitive to the number of dark matter particle produced. It is therefore useful to define

$$r_{\text{inv}} \equiv \frac{\langle \#\text{ of invisible hadrons}\rangle}{\langle \#\text{ of visible hadrons}\rangle}. \tag{5}$$

Where r_{inv} is the average fraction of dark matter particles produced by dark shower and hadronization. In Monte Carlo simulations, r_{inv} can be interpreted as the average probability that a dark hadron is stable.

In order to understand the range of r_{inv} that can be expected from a realistic model, take the the isospin $U(1)_{1-2}$ preserving case as an example: the two diagonal mesons are unstable, and the two off-diagonal mesons are stable. Assuming the hadronization process is flavor blind, *i.e.*, the masses are degenerate, and ignoring baryon production (which is suppressed by a factor of $1/N_c^2$), the average proportion of the stable and unstable hadrons will be equal, implying $r_{\text{inv}} \simeq 0.5$. For this scenario, the invisible ratio r_{inv} can be increased significantly by adding more flavors, since this enlarges the number of off-diagonal mesons by $N_f(N_f - 1)$ while only increasing the number of diagonal mesons by N_f.

This naive counting breaks down when there is mass splitting between the flavors. In the Lund string model, fragmentation into heavier quark pairs is suppressed a tunneling factor [30]

$$T = \exp\left(-\frac{4\pi|m_1^2 - m_2^2|}{\Lambda_{\text{dark}}^2}\right). \tag{6}$$

For large splitting $m_2^2 - m_1^2 \gg \Lambda_{\text{dark}}^2$, $\chi_2^\dagger\chi_2$ fragmentation becomes suppressed and fewer off-diagonal mesons will be produced, thus decreasing r_{inv}. We see that it is easy to adjust r_{inv} to take on any value between $(0, 1)$. The exponential dependence on the fragmentation process implies that the value of r_{inv} is very sensitive to small splittings of the mass parameters.[2] Clearly, r_{inv} will be highly model dependent – given our lack of knowledge about the details of the dark sector, we advocate to treat this as a free parameter when performing a search for semi-visible jets.[3]

Given potentially small coupling between dark sector and the SM, one may worry that the life-times of the stable mesons may be too long to sufficiently decay back to QCD hadrons. Since the diagonal mesons decay through an off-shell Z', one could estimate the decay rate as

$$\Gamma_{\chi^\dagger\chi} \sim \frac{(g_{Z'}^{\text{dark}} g_{Z'}^{\text{SM}})^2}{2\pi M_{Z'}^4} m_d \left|\langle 0|J_{\text{dark}}^\mu|\chi^\dagger\chi\rangle\right|^2 \tag{7}$$

[2] For the $U(1)_{1+2}$ baryon number preserving case, similar mass suppression factor for r_{inv} applies in addition to a $1/N_c^2$ suppression for baryon production.

[3] In order to simulate variations in r_{inv}, each hadron produced from the dark hadronization has a probability r_{inv} to be a stable hadron. The unstable hadrons will be forced to decay into a $u\bar{u}$ or $d\bar{d}$ pair.

Assuming the meson matrix element is simply of order $\Lambda_{\rm dark}^2$ and that $m_d \sim \Lambda_{\rm dark}$, we can obtain the average decay length of the diagonal mesons (assuming there are four light flavors the meson can decay into)

$$\left(\frac{c\tau}{0.1\ \rm mm}\right) \sim \frac{10^{-4}}{(g_{Z'}^{\rm dark} g_{Z'}^{\rm SM})^2}\left(\frac{M_{Z'}}{3\ \rm TeV}\right)^4\left(\frac{\Lambda_{\rm dark}}{20\ \rm GeV}\right)^5 \quad (8)$$

For a 3 TeV Z' and a confinement scale $\Lambda_{\rm dark}$ around 20 GeV, the average boost of the mesons from the Z' decays are dictated by the dark shower and is roughly $\sim$ 10. This gives a millimeter decay length at colliders. It is certainly possible to take advantage of such slightly displaced vertices, but this is highly model independent and will strongly dependent on detector fake rates and non-perturbative QCD background from long-lived hadron productions. We will err on the conservative side and ignore potentially useful variables from long-lived decays.

At colliders, the Z' will be produced through quark annihilations. Afterward, the Z' may decay into the dark sector or back to the SM through the same coupling as its production. The total decay width of the Z' resonance is given by

$$\frac{\Gamma}{M_{Z'}} = \frac{1}{3}\frac{(g_{Z'}^{\rm dark})^2}{4\pi} + 2\frac{(g_{Z'}^{\rm SM})^2}{4\pi} \quad (9)$$

We will work in the narrow width approximation, thus we put an upper bound of 10% on the relative width

$$0.01 \geq \left(\frac{\Gamma}{M_{Z'}}\right)^2 \geq \frac{1}{6\pi^2}(g_{Z'}^{\rm SM} g_{Z'}^{\rm dark})^2 \quad (10)$$

We are interested in the scenario where there are enough Z' decaying into semi-invisible jets for LHC searches to be relelvant. The cross-section times branching ratio is proportional to $(g_{Z'}^{\rm SM} g_{Z'}^{\rm dark})^2$. We see that the narrow width limit puts a mild constraint on the number of signal events seen at the LHC. ** (Hopefully) We will see that there is still a large parameter space that the LHC is sensitive to (to be updated...) **

TL: needs to be updated

We now have everything we need to define the parametrization for the LHC simulation – see Table II. There are the portal parameters: the production cross section and mass of the Z' (assuming 100% branching ratio into the dark sector). In order to parametrize the relevant physics of the dark sector, we assume that all the light particles in the dark sector are degenerate in mass – the LHC is insensitive to whatever mass splittings lead to the variations in $r_{\rm inv}$. In addition, we need $\alpha_d(\mu)$ to determine the dark shower strength along with $r_{\rm inv}$. This gives a finite parameter space that can be used to define a set of search strategies along the lines of Simplified Models.

In order to perform a detailed collider study, Z' events are simulated for the 14 TeV LHC using the `PYTHIAv8.185` hard matrix element and subsequently shower. The default `CTEQ6` parton distribution functions are employed [26, 27, 31]. The Z' is produced via $u\bar{u}, d\bar{d} \to Z'$ through the baryon number coupling. The Z' is then forced to decay into scalar dark sector quarks which then undergo the dark shower using the built in Hidden Valley Pythia module [?], modified to include the running of $\alpha_{\rm dark}$. The dark sector then hadronized into mesons with mass m_d. Each meson will have a probability $r_{\rm inv}$ to be a dark matter particle. The non-dark matter particles are then forced to decay to $u\bar{u}$ or $d\bar{d}$ through an off-shell Z'. Just like in QCD, the various baryon/meson could potentially decay into one another. We neglect these decays in our simplified treatment. After hadronization and decays, the resulting particles are processed through `DELPHES 3.1.2`, with the default CMS settings [32], that includes particle flow. The resulting jets are clustered using anti-k_T algorithm with $R = 0.5$ [33].

[TC: We need to find a place to discuss the correlation with the MET and the second fat jet.]

We recluster $R = 0.5$ jets into two large jets using the Cambridge/Achen algorithm with $R = 2.4$ [34]. Denote the two final large jets by j_1, j_2, with four momenta p_1, p_2. One can then perform a resonance search using the invariance mass $M_{jj}^2 = (p_1 + p_2)^2$. However, when there are significant number of dark matter particles produced in the shower, the M_{jj} variable will degrade significantly due to the large amount of missing information. One can improve the variable by considering the transverse mass instead, defined as

$$M_T^2 = m_{jj}^2 + 2\left(\sqrt{m_{jj}^2 + p_{Tjj}^2}\,\not{E}_T - \vec{p}_{Tjj}\vec{\not{E}}_T\right) \quad (11)$$

Note that $M_{jj} \geq M_T \geq M_{Z'}$ in a detector with perfect resolutions. Figure 2 shows the distribution of M_{jj}, M_T and $M_{\rm MC}$ after event selection. $M_{\rm MC}$ is the reconstructed $M_{Z'}$ computed from all the reclustered jets and the invisible dark matter. M_T in general shows a more prominent peak and is closer to the true level $M_{\rm MC}$. For $r_{\rm inv} \simeq 0.5$, the signal degrades significantly and the improvement from using M_T is lost.

To study the exclusion and discovery potential for a resonance search, we simulated 60×10^6 QCD events matched up to four jets. The matrix element computation is done using `Madgraph 5` and the matching and showering is done in `PYTHIAv8.185`, the detector simula-

	description	benchmark
$\sigma_{pp\to Z'}$	production cross section	through $U(1)_B$
$M_{Z'}$	Z' pole mass	3 TeV
m_d	dark hadron masses	10 GeV
$\alpha_d(\mu)$	running dark shower coupling	$\alpha_d(1\ \rm TeV) = 0.2$
$r_{\rm inv}$	the ratio of invisible to visible content from dark hadronization	0.3

TABLE II: Parametrization of Dark Shower Models

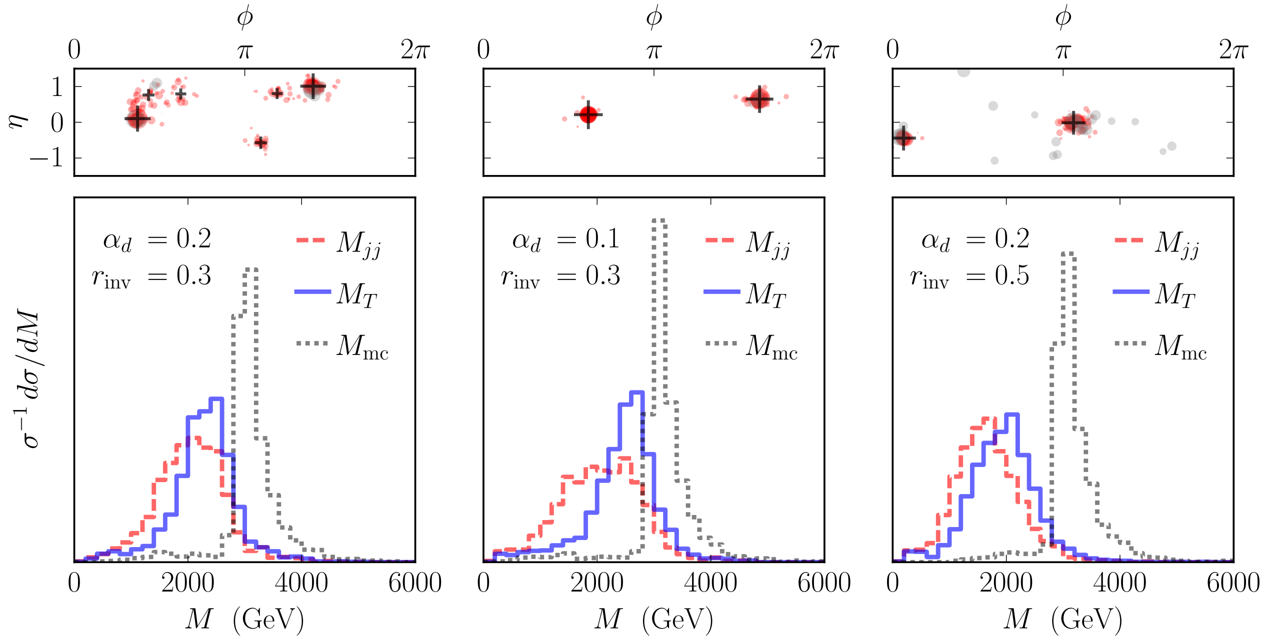

FIG. 2: Different mass variables for the signal events. M_{jj} is the mass of the two large reclustered jets, M_T the transverse mass, and M_{MC} the reconstructed $M_{Z'}$ using all the dark matter particles from Monte Carlo.

tion is the same as the signal. For the signal, we vary $M_{Z'}$ in increments of 500 GeV, and generated 5000 events for each signal point with the parameters in Table II, We apply the following selection criterion to discriminate signal from background

- At least two $R = 0.5$ anti-k_T jets with $p_T > 200$ GeV and $|\eta| < 2.4$, and $\not{E}_T > 200$ GeV (trigger)
- Recluster jets into two $R = 2.4$ CA jets, j_1 and j_2
- Cut on the rapidity difference, $|y_{j_1} - y_{j_2}| < 2.0$

The initial selection is done as a trigger selection. An addition cut on the rapidity different is applied since the signal event tends to be central. After all the selection cuts, we perform a bump hunt on the M_T variable. Since our $\not{E}_T$ is mild, the most dominant background is QCD. $t\bar{t}$ and $W + j$ backgrounds at large $\not{E}_T$ can be easily removed by imposing a lepton veto. We checked that $Z + j$ backgrounds where (**not yet checked**) the Z decays into neutrinos are subdominant and have highly suppressed M_T. **TL: will eventually mention Z and ttbar background**

TL: cite CMS MET work group? mention validation? TC: Yes. Just say we validated against CMS XX. For the background, $M_T \simeq M_{jj}$ and its behavior is dominated by the pdfs. Following dijet resonance searches at ATLAS and CMS [35, 36], we find that the resulting distribution is well described by the an analytic expressions

$$f(x) = p_0 \frac{(1-x)^{p_1 + p_2 \ln x}}{x^{p_3 + p_4 \ln x}} \qquad x = \frac{M_T}{\sqrt{s}} \tag{12}$$

Given the QCD cross-sections computed from `PYTHIA8`, and assuming the QCD background follows the obtained fit exactly, we computed the exclusion and discovery potential for our signal benchmark. A simple log-likelihood analysis is performed. Figure 3 show the the expected exclusion and discovery potential using 100 fb^{-1} of 14 TeV LHC data as a function of $m_{Z'}$ for our benchmark model (Table II). The production cross-section for a Z' with the same coupling as the Standard Model Z (SSM) or photon (QED) is shown as a reference. For Standard model like coupling, Z' of up to 4 TeV can be excluded, and a 5σ discovery may be possible with a $m_{Z'}$ up to 3 TeV. We have also included the exclusion potential using 3000 fb^{-1} of 14 TeV data, and up to 5 TeV Z' with Standard Model couplings can be excluded.

One should be cautioned that, due to limited computation capability, we were not able to generate enough QCD backgrounds with large $\not{E}_T$. Furthermore, the subdominant $t\bar{t}$ backgrounds and electroweak process are neglected. However, none of the Standard Model background would exhibit resonance behaviors at large M_T, and our search strategy should remain effective for probing hidden sectors with new ∼TeV messengers. **TC worries that we are ending this section by saying that we didn't do a good job instead of a high note.**

With the LHC 14 TeV data taking on the horizon, it is important to have a program of searches that cover as wide a range of new physics scenarios as possible. The work presented in this letter opens up new approaches for the discovery of hidden sector physics within the context of resonance searches. In particular, the focus was on dark sector showers that result in novel jets that are

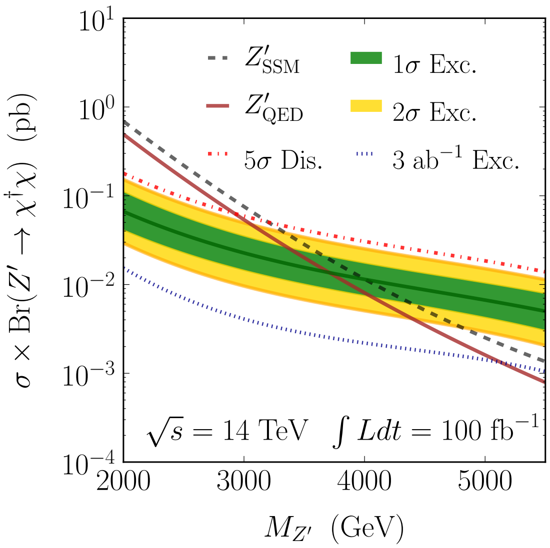

FIG. 3: Expected $\sigma \times$ Br exclusion and discovery for our signal benchmark. The grey curve shows the production cross section for a Z' with the same coupling as the standard model Z. The brown curve shows the cross section for a Z' with QED coupling

composed of Standard Model hadrons and dark matter. We argued that this is a generic signature that could arise from a large class of strongly coupled dark matter models. Furthermore, we gave a simplified parameterization that allows for a systematic treatment of the signature space of possibilities. Finally, we demonstrated that a "bump hunt" in a simple kinematic variable could be performed on a data set preselected with a minimal set of cuts. Discovery reach and exclusion limits were provided for the 14 TeV LHC.

There are two main extensions that can be explored and will require new strategies beyond the one discussed here. First, the restriction that the only Standard Model states produced can be lifted. For example, the shower could also contain leptons and photons. This allows one to continuously dial between the signatures of this model and those of models that result in "lepton jets." This would be useful to unify the approaches between these seemingly disparate class of searches.

The other extension is the production channel. Here we assumed one simple portal, but many others are possible. For example, the dark quarks could be produced as the decay products of a new Higgs boson that is produced in association with the Standard Model Z^0. This would require an entirely different search strategy. Additional variables using jet substructure or displaced vertices will further improve the discovery potential for more specific models. In particular, one might be able to use the events themselves to make Bayesian inferences about the missing energy vector, thereby sharpening the peak in a bump hunt. Exploring the reach for such a class of new production modes exploiting novel variables is left for future work.

Given that the LHC is beginning the long process of turning back on, now is the perfect time to understand the large range of possibilities in order to make the most of the data. Non-trivial dynamics in the dark matter sector is one of the many fantastic and unexpected way that new physics could emerge. This letter provides a simple approach that allows us to prepare for that possibility.

Acknowledgments

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I. NEED TO CITE

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