

# LHC signals for a SuperUnified theory of Dark Matter

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**ABSTRACT:** A new theory of WIMP Dark Matter has been proposed, motivated directly by striking Data from the PAMELA and ATIC collaborations. The WIMP is taken to be charged under a hidden gauge symmetry  $G_{\text{Dark}}$ , broken near the GeV scale; this also provides the necessary ingredients for the “exciting” and “inelastic” Dark Matter interpretations of the INTEGRAL and DAMA signals. In this short note we point out the consequences of the most straightforward embedding of this simple picture within low-energy SUSY, in which  $G_{\text{Dark}}$  breaking at the GeV scale arises naturally through radiative corrections, or Planck-suppressed operators. The theory predicts major additions to SUSY signals at the LHC. A completely generic prediction is that  $G_{\text{Dark}}$  particles can be produced in cascade decays of MSSM superpartners, since these end with pairs of MSSM LSP’s that in turn decay into the true LSP and other particles in the dark sector. In turn, the lightest GeV-scale dark Higgses and gauge bosons eventually decay back into light SM states, and dominantly into leptons. Therefore, a large fraction of all SUSY events will contain at least two “lepton jets”: collections of  $n \geq 2$  leptons, with small angular separations and GeV scale invariant masses. Furthermore, if the Dark Matter sector is directly charged under the Standard Model, the success of gauge coupling unification implies the presence of new long-lived colored particles that can be copiously produced at the LHC.

**KEYWORDS:** Cosmology of Theories beyond the SM, Supersymmetry Breaking, Gauge Symmetry.

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## 1. First hints for dark matter and new physics?

Recent years have seen a growing body of astrophysical signals hinting at the existence of dark matter:

- PAMELA finds an excess of the positron fraction in energies from  $\sim 10 \rightarrow 50$  GeV [1], confirming earlier excesses seen at HEAT [2, 3] and AMS-01 [4]. ATIC sees an excess in  $e^+$  or  $e^-$ , going all the way out to energies of order  $\sim 500 - 800$  GeV [5]. Finally, the WMAP “haze” [6, 7] can be explained by a similar flux of  $e^+/e^-$  from the galactic center, synchrotron radiating in the galactic magnetic field, which could arise from dark matter annihilations [8, 9]. This interpretation of the WMAP Haze predicts a large signal for GLAST (now FERMI), from the inverse Compton scattering of the  $e^+/e^-$  off starlight, and will be tested very soon. At zeroth order, these signals are all consistent with each other and with an interpretation in the terms of reasonable Dark Matter candidates annihilating into SM states with a reasonable annihilation cross-section.
- The INTEGRAL experiment detects a 511 KeV emission line from the galactic center [10–12], consistent with the injection of  $\sim$  few MeV positrons. Naively the mass scale here is very different than that associated with the above anomalies, but if the Dark Sector contains a number of nearly degenerate states with small splittings  $\sim$  few MeV, as in the framework of exciting dark matter, (XDM) [13], then these positrons could also arise from DM annihilation.

- The DAMA signal [14], which is still compatible with the null results of the other DM experiments within the framework of inelastic dark matter (iDM) [15–17], with  $\sim 100$  KeV splittings between dark matter states, not too much smaller than the splittings already required by XDM for the INTEGRAL excess.

While there may be alternative explanations for some of these anomalies (for instance, pulsar wind nebulae for the local electronic excesses [18]), the multiple sources, particularly for high energy electrons/positrons both nearby and in the galactic center, invite the consideration of a connection to dark matter. If we do, we are immediately led to a number of qualitative lessons:

- (0) The most obvious lesson is that there is weak-scale Dark Matter and it is annihilating into the Standard Model with a sizeable cross-section. Thus for instance, the DM can't be a gravitino in low-energy SUSY.
- (I) All the fluxes resulting from DM annihilation are proportional to  $n_{\text{DM}}^2 \sigma_{\text{ann}}$ . Using typical values for  $n_{\text{DM}}$ , the PAMELA/ATIC data seem to require a  $\sigma_{\text{ann}}$  which is  $\sim 100$  times bigger than what one would expect from ordinary WIMPS [19–21]. Most interpretations so far instead assume that the relevant  $n_{\text{DM}}^2$  might be underestimated, but, in our view, such large “boost factors” seem implausible. Instead, one has to explain how the annihilation cross-section can be so large. This motivates the thought the DM is coupled to new light states, with a mass near  $\sim 1$  GeV, and that exchange of these states with the slowly moving DM particles gives a Sommerfeld enhancement needed to boost the cross-section [22].<sup>1</sup> Such light bosons yield annihilation channels that can produce copious leptons without excessive pions and anti-protons [23, 24]. Moreover, this scale is interesting, because a lighter sector might also play a role in explaining the INTEGRAL and even DAMA signals.
- (II) The ATIC data in particular suggest that the Dark Matter particle is at least as heavy as 500-800 GeV [21, 25]. If, as is common in most extensions of the Standard Model motivated by naturalness, the Dark Matter is the lightest state of new physics, having the *bottom* of the spectrum near 800 GeV begins to make the theory very un-natural indeed. If we want to hold on to the idea of naturalness, it had better be that the DM is *not* the lightest state of new physics, but instead some state with vector-like quantum numbers under the Standard Model, which is stable or sufficiently long-lived as a consequence of a new exact or approximate symmetry.

Starting from these qualitative lessons, [22] proposed a simple theory for explaining all the Dark Matter anomalies: the Dark Matter arises from a multiplet of vector-like states, with some or all of their flavor symmetry gauged. We show that this picture for Dark Matter is naturally embedded in extensions of Standard Model motivated by solving the hierarchy problem and particularly with low-energy SUSY. Indeed, when this set-up is

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<sup>1</sup>The Sommerfeld enhancement was first explored in the context of dark matter in [44, 45], arising from weak interactions for multi-TeV WIMPs. More recently, it has been connected to signals from “Minimal Dark Matter,” [46] including PAMELA signals [20].

embedded in the rubric of low-energy SUSY, it adds two exciting ingredients to discovery physics at the LHC, associated directly with supersymmetric cousins of the lessons (I) and (II) above:

- SUSY(I) If there are new light gauge states, it is reasonable to imagine that the SUSY particles in this new sector are also much lighter than ours, and thus, the LSP in the other sector is lighter than ours. Thus, our LSP will decay into the Dark sector. But, as argued in [22], at least some states in the Dark sector should decay directly into Standard Model states; as we will see, these decays will naturally be predominantly to  $e^+e^-/\mu^+\mu^-$ , and may be associated with displaced vertices. The lepton pairs will be unusual; their invariant mass will be  $\sim \text{GeV}$ , and given that the parent particles in the Dark sector will be very highly boosted with a  $\gamma \sim 10^2$ , in a typical decay the leptons will be also be produced with tiny opening angles. We'll refer to such groups of high  $p_T$  leptons with small opening angles and  $\sim \text{GeV}$  invariant masses as “lepton jets”. Thus, a large fraction of SUSY events at the LHC should be accompanied with at least *two* “lepton jets”.
- SUSY(II) It is possible that the Dark Matter is directly charged under the Standard Model, or more generally, that there are states charged under the symmetry that keeps the Dark Matter stable that are also charged under the Standard Model. If we wish to preserve the supersymmetric picture of gauge coupling unification, these states should come in multiplets that also contain other colored particles. These colored particles can be long-lived(though short-lived enough cosmologically).

While our discussion is framed within the context of low-energy SUSY, some of the conclusions hold in a wider class of theories for new physics. The signals associated with decays into the dark sector and back follow in any theory with a particle charged under the SM that is nonetheless stable in the absence of a small coupling to the Dark Sector, while the new colored states should be expected in any picture in which the Dark Matter is charged under the Standard Model and gauge coupling unification is taken seriously.

## 2. The minimal superdark moose

The discussion of [22] was mainly concerned with elucidating a picture of the Dark Matter sector, but ideally this picture should emerge from a theory that also solves the hierarchy problem. There are essentially two classes of theories we consider, and they are shown in figures 1a,b.

The model with the minimal field content (figure 1a), contains no fields in the low energy theory which are simultaneously charged under both  $G_{\text{SM}}$  and  $G_{\text{Dark}}$ . The dark matter must be stable (on cosmological timescales at least), and this could arise from any range of accidental or exact discrete symmetries  $G_\chi$ , global or gauged. We assume the Dark Matter particle has mass of order the weak scale, while many or all of the other fields charged under  $G_{\text{dark}}$  have masses  $O(\text{GeV})$ , a scale whose origin we shall come to. A question we must address is why the dark matter mass is of order the weak scale if the

sector is largely disconnected from the standard model. This could arise naturally if the Dark Matter mass arises from the same physics that sets the MSSM  $\mu$  term, linking the scales to each other, for instance via an NMSSM-type mechanism. We will assume for the moment that the only low-energy connection between the standard model sector and the GeV-scale particles comes through a mixing between the dark sector gauge fields and the standard model gauge fields. Presumably, such a mixing comes from fields which are charged under both  $G_{\text{SM}}$  and  $G_{\text{Dark}}$ , but these may be extremely heavy, even string states.

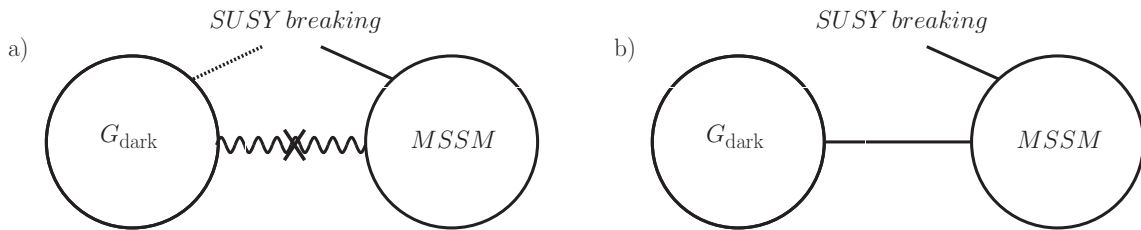
Given that the kinetic mixing needs some states charged under both  $G_{\text{Dark}}$  and  $G_{\text{SM}}$ , a second natural possibility is that there are “link” fields in the low-energy theory at the TeV scale, as in the minimal SuperDark Moose of figure (1b). The links can be neutral under  $G_\chi$ , in which case they will be unstable (unless protected by yet another symmetry). If the links are charged under  $G_\chi$ , and there are no other  $G_\chi$  charged states charged under  $G_{\text{Dark}}$ , then the lightest of the link fields will be the Dark Matter. More generally, if there are also fields charged only under  $G_\chi$  and  $G_{\text{Dark}}$ , the Dark Matter will be some linear combination of these states and the link fields, which can mix after electroweak symmetry breaking.

The idea that dark matter could contain interactions with some new long-distance force has a significant history. The consequences of a new U(1), mixing with hypercharge was first explored in [26], and has been studied extensively within “mirror dark matter” [27]. More recently, forces have been invoked for more phenomenological purposes, in particular in “exciting dark matter” [13] (which is relevant to our discussion here), “secluded dark matter” [28], MeV-scale dark matter [29, 30], and WIMPlless dark matter [31].

The gauge structures in figures 1 in particular, are very similar to those used in [32, 31], where the radiative effects were used to generate dark matter at new mass scales, that nonetheless had the relic abundance expected for a WIMP. Here, our dark matter particle is still weak-scale, but the radiative effects will generate mass scales for  $G_{\text{dark}}$  breaking in a similar fashion.

As we’ll shortly see, the addition of SUSY and SUSY breaking makes it very natural for the  $G_{\text{Dark}}$  symmetry to be broken with dark gauge boson masses at the  $\sim M_{Z_{\text{Dark}}} \sim \alpha M_Z \sim \text{GeV}$  scale. As in [22], this then radiatively induces splittings between the various DM states of order  $\delta M_{\text{DM}} \sim \alpha M_{Z_{\text{Dark}}} \sim \text{MeV}$ , automatically providing the necessary ingredients for the XDM and iDM interpretations of the INTEGRAL and DAMA signals. There are other possible sources of splittings of the same size. For instance, if the  $G_{\text{Dark}}$  quantum numbers of the Dark Matter are such that the first coupling to Dark Higgses arises from dimension 5 operators (analogously to neutrino masses in the Standard Model), then if these operators are generated at the TeV scale, we will get splittings  $\sim \text{GeV}^2/\text{TeV} \sim \text{MeV}$  as well.

We should emphasize that from a top-down point of view, there is no particular rationale for these new particles, as they don’t in themselves play an obvious role in solving the outstanding mysteries of particle theory, such as the hierarchy problem. Having said that, introducing additional vector-like states charged under another gauge symmetry is not particularly exotic, and indeed such “moose” or “quiver” structures for gauge theories arise very naturally in many more complete frameworks for UV physics such as string theory. At any rate, our motivation for introducing these structures comes entirely from astrophysical Data and not the desire to engineer exciting collider phenomenology. Nonetheless, as we



**Figure 1:** The minimal supersymmetric model (a) and the minimal SuperDark Moose (b).

will see, this set-up incorporates all the physics we have discussed while further providing a natural explanation for why  $M_{Z_{\text{Dark}}} \sim \alpha M_Z$  is near the GeV scale. It can also impact LHC collider phenomenology in a dramatic way.

## 2.1 Natural scale generation and low-energy SUSY breaking

We would like to have a natural understanding of why the scale of  $G_{\text{Dark}}$  breaking is low. If we have high-scale SUSY breaking mediated by gravity or its cousins like anomaly mediation, we would instead expect that the soft masses in all the sectors are comparable. Thus we are led to imagine SUSY breaking and mediation at a lower scale.

Suppose the Dark Matter fields have soft masses  $M_S$  of the same order as the MSSM fields  $M_S \sim 100$ 's of GeV, and suppose further that the  $G_{\text{Dark}}$  sector only get SUSY breaking from DM loops. Then, we naturally induce SUSY breaking soft masses at two-loops

$$M_{\text{SoftDark}}^2 \sim \left(\frac{\alpha}{4\pi}\right)^2 M_S^2 \quad (2.1)$$

in the dark sector, leading naturally to symmetry breaking with  $M_{Z_{\text{Dark}}} \sim \frac{\alpha}{4\pi} M_S$ . Therefore, we get the needed hierarchy of scales with  $G_{\text{Dark}}$  breaking at the 100 MeV - 1 GeV scale naturally.<sup>2</sup>

Why would the dark matter have soft masses of  $O(100 \text{ GeV})$ ? If we are assuming that whatever generates the  $\mu$  term for the Higgsinos is responsible for the scale of the dark matter mass, then it is natural for it to generate a  $B_\mu$  term as well, in which case the dark matter fields serve as SUSY breaking messengers for  $G_{\text{Dark}}$ , generating soft masses  $O(\alpha_{\text{Dark}} m_{\text{SUSY}}/4\pi)$ . If the dark matter mass scale is an accident, or, somehow generates a weak scale mass without a  $B_\mu$  term, it is possible for supersymmetry breaking to be transmitted to the dark sector through non-renormalizable operators.

This setup is extremely natural if we take the Dark Matter to be charged under the SM as well, within the context of some low-energy SUSY breaking scenario, such as gauge mediation. In this case, the DM would also pick up a “ $\phi^*\phi$ ” soft mass of the same order as the other MSSM fields, but the dark states uncharged under the SM would only get soft masses from DM loops. Since the gravitino is the LSP, if we wish to preserve WIMP dark matter we need some extra fields in any case, and gauge mediation makes a cascade of radiatively generated scales very natural.

<sup>2</sup>A similar approach was used in [32] to achieve MeV-scale dark matter.

As we have already mentioned, the mass of the DM particle can be fixed to near the weak scale by the same mechanism that fixes  $\mu$  to be near the weak scale. A popular way of doing this is through the addition of a singlet field  $S$  as in the NMSSM, it is then natural to have  $S$  couple in the superpotential  $\kappa SH_u H_d + \kappa' S F F^c$ . Then the vev of  $S$  will determine both  $\mu$  and the mass of the Dark Matter particle. It is amusing to note that usually in gauge mediation, it is difficult to make the NMSSM work in detail, since  $S$  fails to get a large enough negative soft mass from simply coupling to  $H_u H_d$ . However an additional coupling to some  $(5 + \bar{5})$ 's can increase this negative mass<sup>2</sup> significantly and give a viable solution to the  $\mu$  problem [33].

Even the dark matter does not acquire a large soft mass, and is not charged under the SM at all, we can still get the  $\sim \text{GeV}$  scale for the soft masses in a natural way in the context of quite high-scale gauge mediation, with the  $\sim \text{GeV}$  gravitino mass, and a generic  $\sim \text{GeV}$  size gravity-mediated SUSY breaking. This is about the largest magnitude tolerable for comfortably solving the MSSM flavor problem, since the flavor splittings are  $\sim \delta m^2/m^2 \sim (1 \text{ GeV}/100 \text{ GeV})^2 \sim 10^{-4}$ . It also represents a reasonably natural messenger scale close to the GUT scale. But while this ‘‘Planck slop’’ is a small perturbation in the MSSM sector, it can generate  $\sim \text{GeV}$  soft masses in the Dark sector, leading again to  $G_{\text{Dark}}$  breaking at the GeV scale.

Finally, if there are link fields with masses and soft masses in the near the  $\sim \text{TeV}$  scale, then they will also act as ‘‘messengers’’ for the  $G_{\text{Dark}}$  sector, again generating dark soft masses at two-loops, naturally near the  $\sim \text{GeV}$  scale.

## 2.2 Shedding light on $G_{\text{Dark}}$

Let us now examine how the  $G_{\text{Dark}}$  fields communicate with the MSSM sector. The success of BBN tells us that we shouldn't have any massless states in the dark sector; it is most natural to assume that all the lightest new states have a mass in the same  $\sim \text{GeV}$  range, and that they can only decay back to SM states. Indeed, this is necessary for the interpretation of the PAMELA/ATIC data given in [22], since we assume that the DM annihilations primarily occur into the light states in the dark sector, and these must decay back to  $e^+e^-$  a large fraction the the time to explain the observed signals. Thus we have to examine the leading interactions between the dark sector and the SM, and determine how the lightest states in the dark sector can decay into SM states.

Let's begin by considering how the bosonic states in the new sector-Higgses and gauge bosons-couple to the SM. These are necessarily produced in DM annihilation, and this part of our discussion holds generally for *any* version of the scenario in [22], whether or not it is supersymmetric. The Lagrangian for these theories is of the form

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Dark}} + \mathcal{L}_{\text{mix}}, \tag{2.2}$$

and we wish to determine the leading interactions possible between the Dark and SM sectors  $\mathcal{L}_{\text{mix}}$ .

For simplicity, let's start by imagining that the new gauge sector has a  $U(1)_{\text{Dark}}$  symmetry with gauge field  $a_{\text{Dark}}^\mu$ . Then, the leading interaction with the Standard Model at

low energies is through kinetic mixing with the photon

$$\mathcal{L}_{\text{mix}} = -\frac{1}{2}\epsilon f_{\text{Dark}}^{\mu\nu} F^{\mu\nu}, \tag{2.3}$$

where of course this coupling would have to arise from a mixing with hypercharge at energies above the weak scale. We also assume that there is a Higgs charged only under  $U(1)_{\text{Dark}}$ , so that in Unitary gauge we get a mass term for  $a_{\text{Dark}}^\mu$

$$m^2 a_\mu^2. \tag{2.4}$$

It is natural to assume that the kinetic mixing is absent in the UV — for instance if  $U(1)_Y$  is embedded in a non-Abelian GUT at some scale. Then the mixing can be generated radiatively by loops of particles — that may include the Dark Matter itself — that are charged under both sectors; this gives  $\epsilon \sim 10^{-3}$  as a reasonable estimate. Actually, in a completely generic model, one might expect this mixing to be enhanced by a large logarithm  $\sim \log(M_{\text{GUT}}/M)$  from a high scale like the GUT scale. However, if we imagine that these new states fill out complete  $SU(5)$  multiplets with colored and uncolored states, we instead get a calculable mixing, with  $\log(M_{\text{GUT}}/M)$  replaced by  $\log(M_{\text{colored}}/M_{\text{uncolored}})$ . If there are no light states in the theory charged under both  $G_{\text{dark}}$  and  $G_{\text{SM}}$ , then very heavy fields (near the GUT scale) would also be expected to generate a mixing, except now, the natural scale is *two-loop*, or  $\epsilon \sim 10^{-6} - 10^{-4}$ , because the split GUT multiplets have only a log-enhanced splitting at low energies.

We can study the physics conveniently by making the the field redefinition  $A^\mu \rightarrow A^\mu + \epsilon a_{\text{Dark}}^\mu$ , which removes the kinetic mixing (and also change the  $a_{\text{Dark}}^\mu$  kinetic terms by an irrelevant  $O(\epsilon^2)$  amount). We thus induce a coupling between the electromagnetic current and  $a_{\text{Dark}}^\mu$ :

$$\epsilon a_{\text{Dark}}^\mu J_\mu^{\text{EM}}. \tag{2.5}$$

Note that this does not imply that the dark matter carries electric charge, as is of course guaranteed by gauge invariance. The linear combination of gauge fields which is Higgsed is precisely that combination which couples to dark matter, while the independent, massless combination couples only to standard model fields.

More generally, we can imagine a non-Abelian  $G_{\text{Dark}}$ , where the dimension 4 kinetic mixing is absent. We can still can get an S- parameter type operator mixing to the photon if there are particles that couple to the other sectors Higgs and the SM; this will give us kinetic mixing operators of the same form but effectively suppressing  $\epsilon$  by a factor of  $(v_{\text{Dark}}/M)^p$  where  $p$  depends on the Higgs quantum numbers. For instance if the Higgses  $\Phi_{\text{Dark}}$  are in the adjoint, we can have operators of the form  $\frac{1}{M} \text{Tr}(\Phi_{\text{Dark}} f_{\text{Dark}}^{\mu\nu}) F_{\mu\nu}$  with  $p = 1$ , while e.g. for an  $SU(2)$  gauge theory with doublet Higgses, the analog of the usual S-parameter operator would have  $p = 2$  etc.

Going to Unitary gauge we will have a collection of Dark Gauge fields  $a_{\text{Dark}i}^\mu$ , and we'll have

$$m_{ij}^2 a_{\text{Dark}i}^\mu a_{\text{Dark}j}^\mu - \frac{1}{2}\epsilon_i f_{\text{Dark}i}^{\mu\nu} F^{\mu\nu}, \tag{2.6}$$

where the  $\epsilon_i$  are naturally  $\sim 10^{-3}$  for an Abelian factor and are further suppressed for the non-Abelian factors. Redefining  $A^\mu \rightarrow A^\mu + \epsilon_i a_{\text{Dark}i}^\mu$ , ignoring the tiny  $O(\epsilon^2)$  kinetic



term corrections for the  $a_i$ , and changing to mass eigenstate basis by diagonalizing  $m_{ij}^2 = U_{iI}^\dagger m_I^2 U_{Ij}$ , we get a coupling to the electromagnetic current

$$\epsilon_I a_{Dark I}^\mu J_\mu^{EM}, \text{ with } \epsilon_I = U_{Ii} \epsilon_i. \quad (2.7)$$

Note that if a U(1) factor is present, in general there will be Higgses charged under both U(1) and non-Abelian factors, so  $m_{ij}^2$  will mix all the spin one particles and the mass eigenstates can all have sizeable U(1) components. Thus, even if there is a single U(1) factor, we can get  $O(10^{-3})$  size couplings of all the massive gauge bosons to the electromagnetic current.

If this spin-1 particle can't decay in its own sector for any kinematical reason, then it will decay through this coupling to the SM. If it is lighter than  $\sim 1$  GeV, then it can't decay to protons and anti-protons, while it could decay to  $K^+K^-$ ,  $\pi^+\pi^-$ ,  $\mu^+\mu^-$  and  $e^+e^-$ . This is encouraging because a huge fraction of these events end up having  $e^+e^-$ , and very few prompt photons from  $\pi^0$  decays, so this is the range we prefer to give the maximal enhancement to the PAMELA/ATIC signal without polluting other channels. Note that the decay length is

$$\tau \sim (\alpha \epsilon^2 m_{Z_{Dark}} N_{\text{decay channels}})^{-1} \sim \left(\frac{10^{-7}}{\epsilon}\right)^2 \text{ cm} \quad (2.8)$$

So, in the case where the mixing between the sectors arises only after dark sector symmetry breaking, these decay lengths can be macroscopic, but otherwise the decays are prompt.

Let us consider the Higgses in the dark sector. They necessarily have an interaction of the form  $m_{\text{light}} h a_\mu^2$  with heavy gauge bosons, we have a variety of possibilities for decays. If the Higgs is heavier than twice the mass of the lightest spin-1 particle, it will decay to them on-shell, which in turn decay to leptons, giving rise to remarkable 4 body decays like e.g.  $h \rightarrow e^+e^-\mu^+\mu^-$ . Alternatively, If the lightest state is spin 1 but the Higgs is lighter than twice this mass, then we will get a decay of  $h$  to the lightest spin 1 plus a single current suppressed only by one power of  $\epsilon$ . Finally, if the dark Higgs cannot decay to any on-shell particles, it will decay through loops of the dark gauge fields and SM leptons to two leptons, with a width suppressed by  $\epsilon^4/(16\pi^2)^2$ , and through off-shell gauge bosons with a parametrically similar width, but with four leptons in the final state. Note that these decays do have a macroscopic length even for  $\epsilon \sim 10^{-3}$ .

If the Higgs mixes with the standard model through an operator  $\kappa \phi^* \phi h^* h$ , it could decay directly into a variety of hadrons if it is heavy enough, or directly to muons, such as described in [23]. The mixing angle with the standard model Higgs should not be naturally larger than  $10^{-6}$  for completely natural parameters [23, 34], which would make direct decays to SM fermions possible (i.e., bypassing the intermediate dark gauge bosons). However, in SUSY, this would arise from the presence of singlet or non-renormalizable operator (for instance arising from such a singlet). In this case, we would expect this to be additionally suppressed. However, we note some decays to pions, kaons and other light hadrons is possible.

Finally the dark sector might also include some light pseudo-goldstone bosons  $\pi$ . If the SM fermions carried a charge under the broken symmetry, then  $\pi$  will decay to the

heaviest allowed particle, otherwise it's decays are to two photons; the couplings are

$$\frac{m_\Psi}{f} \pi \bar{\Psi} \Psi, \frac{\alpha}{4\pi} \frac{\pi}{f} F \tilde{F}. \tag{2.9}$$

Especially in the most natural case where the Dark Matter mass arises from the symmetry breaking associated with the pseudo, we should expect  $f$  near the weak scale, and in both of these cases the decay lengths can be macroscopic.

Note that making the dark sector supersymmetric adds new kinds of particles to the dark sector not explicitly considered in [22]: the DM superpartners, as well as gauginos and new fermions of the  $\sim$  GeV scale dark sector. The new light particles in particular could in principle provide new DM annihilation channels, though these would involve exchange of the heavier DM superpartner and would be suppressed, and more importantly, annihilation to fermions is chirality suppressed, so these will have a very small branching ratio relative to the dark gauge boson channels. Also, in order to have at least some of the vector bosons primarily decay to leptons as required by ATIC/PAMELA, we must ensure that they don't decay into the new dark fermions; this could happen if some of the vectors are lighter than twice the fermion masses, which is perfectly reasonable. Further aspects of the mixing between superpartners in the MSSM and Dark sectors are described in next section.

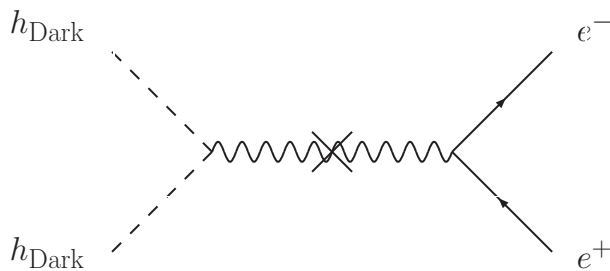
### 2.3 Experimental limits on light Gauge bosons

In our theory we have light  $\sim$  GeV gauge bosons with a tiny coupling to the electromagnetic current; the current experimental limits on such particles (dubbed "U bosons") are discussed and summarized in [29, 30]. Not surprisingly, because this coupling doesn't break any of the approximate symmetries of the Standard Model, the constraints are mild. The strongest constraint comes from the the 1-loop contribution of this particle to the muon  $(g - 2)_\mu$ , which is of order

$$\delta(g - 2)_\mu \sim \epsilon^2 \frac{\alpha}{\pi} \frac{m_\mu^2}{m_{Z_{\text{Dark}}}^2} \sim 10^{-11} \tag{2.10}$$

even for  $\epsilon \sim 10^{-3}$  and  $m_{Z_{\text{Dark}}} \sim 1$  GeV. The sign is the same as the current (small) disagreement between the measured value of  $(g - 2)$  and the SM.

The production of this new gauge boson in any processes is suppressed by a factor of  $\sim \epsilon^2$ , and there is always a background from the same process replacing the on-shell gauge boson by an off-shell photon. Nonetheless one can get an interesting signal since the new gauge boson has a miniscule width, much smaller than any experimental resolution. The best limits discussed in [35] come from low-energy  $e^+e^-$  machines; best of all (because of the largest integrated luminosity) from B-factories. The  $U$  boson is produced in  $e^+e^- \rightarrow \gamma U$ , with  $U$  decaying back to  $e^+e^-$  (though the analysis is essentially the same for  $U \rightarrow \mu^+\mu^-$  as well). Binning the data as a function of the  $m_{e^+e^-}^2$ , the signal would be an excess over the Standard Model background in a single bin; for energies near  $\sim$  GeV, energy resolutions  $\sim$  MeV possible. The analysis of [35] concludes that a limit  $\epsilon \sim 10^{-3}$  could be reached from B-factory data. However, to our knowledge, this search has not been done by any of the collaborations. Needless to say it would be extremely interesting to perform this analysis!



**Figure 2:** Process contributing to thermal equilibrium of the  $G_{\text{Dark}}$  sector.

If there are no signals in the current data, an increase of  $\sim 100$  luminosity at a super-B factory can push the limit on  $\epsilon$  down by another order of magnitude to  $\epsilon \sim 10^{-4}$ . It would be interesting to explore other experimental probes of such light, weakly coupled gauge bosons more systematically.

Note that, as pointed out in [22], a coupling  $\epsilon \sim 10^{-3} - 10^{-4}$  accompanied by  $\sim 100$  KeV splittings amongst Dark Matter states, can explain the DAMA signal. It is intriguing that in this same range we get an interesting contribution to  $(g - 2)_\mu$ , as well as the possibility to detect direct production of the new gauge bosons.

## 2.4 The early universe and the GeV-scale spectrum

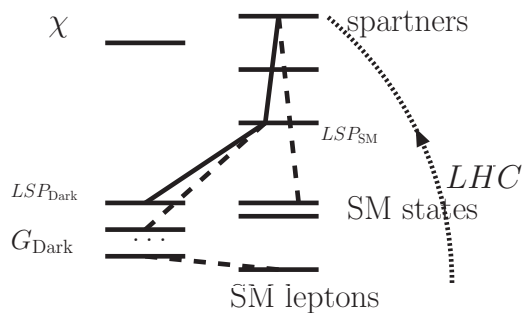
Our focus here is on the LHC phenomenology, so we shall not attempt to describe to complete features of the early universe phenomenology. Rather, we are interested in understanding what the implications of freezeout are on the possible decay chains through the GeV-scale  $G_{\text{Dark}}$  sector.

The dark matter will stay in equilibrium, either via annihilations to  $G_{\text{Dark}}$  gauge bosons (in analogue to the XDM scenario freezeout [13]),<sup>3</sup> or via annihilations to  $G_{\text{Dark}}$  and  $G_{\text{SM}}$  gauge bosons in the case that the DM carries a SM charge as well. Thus, we focus on the equilibrium properties of the light particles. Thus we consider the thermal properties at GeV temperatures, long after the much heavier dark matter has frozen out. The dark Higgses and dark gauge bosons will generally stay in thermal equilibrium with the standard model via s-channel dark gauge boson exchange (figure 2). This process will proceed with a cross section  $\sigma \sim \alpha^2 \epsilon^2 / \text{GeV}^2$ . This will maintain equilibrium between the sectors until the dark particles become non-relativistic.

If the LSP of the dark sector, which we refer to as  $\text{LSP}_{\text{Dark}}$ , is the true LSP (i.e., lighter than the gravitino, as might occur in high-scale gauge mediation), we must check whether it is overproduced in the early universe, but the abundance is easily small enough. For instance, if the  $\text{LSP}_{\text{Dark}}$  is a dark gaugino, t-channel dark Higgsino exchange will allow annihilations into dark Higgses, with  $\alpha^2 / \text{GeV}^2$  cross sections, giving a present abundance  $\sim 10^{-4}$  times critical density.

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<sup>3</sup>Such freezeout has been termed “secluded” dark matter models [28], and similar phenomena occur in “WIMPlless” models [31].



**Figure 3:** Cascade decays into the  $G_{Dark}$  sector and lepton jets. The final decay to leptons can arise at the end of a variety of chains in the  $G_{Dark}$  charged sector.

### 3. Cascade decays into the SuperDark “Hidden Valley”

If there are many particles which are kinematically accessible to the LHC, we must ask: how could such  $G_{Dark}$ -charged states be produced? There are two simple possibilities: we can produce the  $G_{Dark}$ -charged states directly, or we can cascade into them. We will begin with the latter case.

The presence of a new sector of light particles weakly coupled to the Standard Model can have dramatic implications for collider physics, as has especially been explored in recent years by Strassler and collaborators [36–40]. This is particularly the case in low-energy SUSY with unbroken R-parity, since in this case the LSP can reside in the new sector, so that all SUSY events eventually ending up with MSSM LSP’s decay to the new sector. This was discussed at length in the context of supersymmetric “Hidden Valley” theories in [38]. Here we outline what this physics looks like in our case; the principle difference between this scenario and previous studies of “Hidden Valley” phenomenology is that the particular leading interaction between our sector and the dark sector arises through kinetic mixing with the photon. This has important implications for the collider phenomenology, for instance, we do not expect the hidden sector to dominantly decay to heavy flavor Standard Model states. Moreover, because we are motivated by the electronic excesses at PAMELA and ATIC, the mass scale we single out kinematically favors leptons in final states.

We preface this discussion with a comment: since the Dark Matter is not the LSP, R-parity is not needed to keep the Dark Matter stable, and instead another discrete symmetry must be invoked. However, R-parity is still the simplest explanation for the absence of  $B$  and  $L$  violating couplings in the MSSM, so we will continue to assume it is a good symmetry as the simplest possibility, though we will have a few words about R-parity violation as well.

We begin with a bit of nomenclature. We refer to the lightest R-odd particle of the MSSM as  $LSP_{sm}$ . Similarly, we refer to the lightest R-odd particle charged under  $G_{Dark}$  as  $LSP_{Dark}$ . A priori, we make no assumption as to whether the gravitino is the “true” LSP or not. As it will happen, the phenomenology is most generically interesting when the gravitino is the true LSP, as in low-scale gauge mediation, although much interesting phenomenology can arise even if the  $LSP_{Dark}$  is the LSP.

The basic picture of the phenomenology is shown in figure 3. We assume that LHC

SUSY production occurs as in a standard SUSY scenario. This proceeds to cascade down to the  $LSP_{\text{SM}}$  and visible matter. If the SUSY breaking scale is sufficiently high (which we shall argue should generically be the case), then the  $LSP_{\text{SM}}$  must decay through the hidden sector to reach the  $LSP_{\text{Dark}}$ . Because the connection to the standard model goes through the gauge mixing, the states heavy enough to decay to the dark gauge bosons will do so, and those that are lighter will proceed through loops or off shell dark gauge bosons to produce leptons as well. As a consequence, a generic feature of the decay will be “lepton jets,” i.e., sets of  $n \geq 2$  highly boosted leptons with low ( $\sim \text{GeV}$ ) invariant mass.

### 3.1 Decay zoology

Although the myriad possibilities cannot be listed exhaustively, we attempt to discuss the most important features. The same physics that gives rise to the  $\epsilon$  kinetic mixing between the hidden gauge field and the photon, will give rise to a mixing between the hidden gaugino  $\eta$  and  $\chi_0$

$$\epsilon' \bar{\eta} \bar{\sigma}^\mu \partial_\mu \chi_0, \tag{3.1}$$

and so the  $\chi_0$  will have a small mixing with the dark sector. It is important to note that in most MSSM models, the gauginos are relatively pure states (i.e., not significant mixtures with the Higgsinos). This is because the mixing terms arising from Higgs vevs are generally much smaller than MSSM SUSY breaking masses (a reflection of the well-appreciated tuning necessary for the MSSM Higgs sector). This is not expected to be the case in  $G_{\text{Dark}}$ , where most likely the fermionic states will be large mixtures of dark-Higgsino and dark-gaugino.

Let us begin with the case where the  $LSP_{\text{SM}}$  is a gaugino. In this case, because of the mixing term, we expect a decay such as  $\chi_0 \rightarrow h_{\text{Dark}} \chi_{\text{Dark}}$ , where  $\chi_{\text{Dark}}$  may or may not be  $LSP_{\text{Dark}}$ . Subsequently, we will have  $h_{\text{Dark}}$  decay to leptons, either through on-shell, off-shell, or loops of, dark gauge bosons. If  $\chi_{\text{Dark}}$  is not the  $LSP_{\text{Dark}}$ , we expect it to decay to  $LSP_{\text{Dark}}$  via on- or off-shell dark gauge boson emission (such as in the case of non-Abelian  $G_{\text{Dark}}$ ). If the gravitino is the true LSP, we expect the  $LSP_{\text{Dark}}$  to decay further to  $\tilde{\psi}_{3/2}$  and a dark gauge boson or dark Higgs, which then subsequently will decay to additional leptons.

Alternatively, we can consider a case where the  $LSP_{\text{SM}}$  is a sfermion  $\tilde{f}$ . In this case, we will have  $\tilde{f} \rightarrow f \eta_{\text{Dark}}$ , where  $\eta_{\text{Dark}}$  is one of the mixed gaugino-Higgsino states of  $G_{\text{Dark}}$ . If  $\eta_{\text{Dark}}$  is the true LSP, then this will appear similar to gauge mediation. However, we still expect some decays to states  $\eta_{\text{Dark}}$  which are not the  $LSP_{\text{Dark}}$  (of the dark Higgsino/gaugino mixture), which then decay to the  $LSP_{\text{Dark}}$ . If we are in a scenario such as low-scale gauge mediation, then, again, we have  $LSP_{\text{Dark}} \rightarrow a_{\text{Dark}} \tilde{\psi}_{3/2}$ , followed by  $a_{\text{Dark}} \rightarrow \text{leptons}$ , or, possibly, further cascades in the situation of  $LSP_{\text{Dark}} \rightarrow h_{\text{Dark}} \tilde{\psi}_{3/2}$ , or some other state which decays further in the  $G_{\text{Dark}}$  sector.

In this discussion we have ignored the possibility that the  $LSP_{\text{SM}}$  could instead decay straight to the gravitino. However, this decay width is of order  $m_{\chi_0}^5/F^2$ ; even for the lowest imaginable scale  $F \sim (10 \text{ TeV})^2$ , this is subdominant for  $\epsilon > 10^{-6}$ . If matter/R parity is broken, then there is also a competing  $R_p$  violating decay of the  $LSP_{\text{SM}}$  to SM particles. As usual with  $R_p$  violation, we have to imagine that we are either preserving baryon number

or lepton number. If we are allowing the  $qld, lle$  operators, then their size is constrained minimally by not generating too-large neutrino masses at 1-loop; this makes the couplings small enough that for  $\epsilon \sim 10^{-3}$ , the  $LSP_{\text{SM}}$  would still prefer to decay into the new light sector. Only the purely  $udd$  operators involving all third generation fields can have reasonable coefficients and significantly depress the decay of  $LSP_{\text{SM}}$  into the new sector.

Clearly there are many more combinatorial possibilities one could envision; we have engaged in this brief discussion here only to make it clear that regardless of the identity of  $LSP_{\text{SM}}$ , SUSY events will lead to decays into the Dark sector, and these will in return decay back into leptons in our sector, which we now turn to.

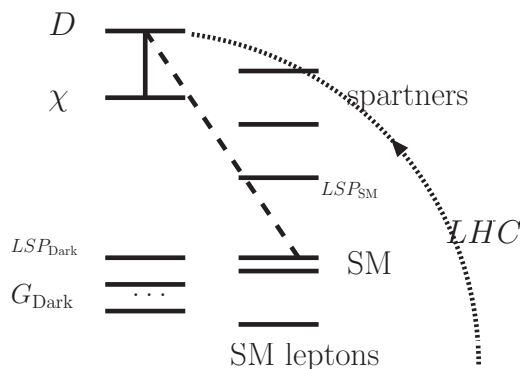
### 3.2 “Lepton jets”

Usually every SUSY event ends with two LSP’s plus visible particles; in our case, the  $LSP_{\text{SM}}$ ’s further decay into the  $LSP_{\text{Dark}}$  that still carries away missing energy, but also goes to the lightest R-even particles that decay back to  $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$  with a large branching fraction. The parent particles in the dark sector are boosted with  $\gamma \sim M_{LSP_{\text{SM}}}/m_{\text{Dark}} \sim 100$ . The decay lengths are as quoted in the section II, multiplied by this  $\gamma$  factor. If  $\epsilon$  is as large as can be consistent with the muon  $(g-2)$  constraints, the decay will not leave a sufficiently large displaced vertex, but with any suppression of  $\epsilon'$  displaced vertices are a distinct possibility. Regardless of the displaced vertices, the lepton pairs will have a small invariant mass  $\sim \text{GeV}$ , and in typical decays, will come out with small angular separation  $\sim 1/\gamma \sim 10^{-2}$ . Thus essentially all SUSY events should include *at least two* pairs (4 leptons total) of high- $p_T$  opposite-charge light particles. In cases where leptons are produced more copiously, it will be difficult to extract resonances from the combinatorial background. Nonetheless, because the splittings in the sector are expected to be  $\sim \text{GeV}$ , we do not expect any reason for the leptons to be particularly soft, except as arises in multibody phase space. Thus, we have the possibility of “lepton jets”: boosted groups of  $n \geq 2$  leptons with low  $\lesssim \text{GeV}$  invariant masses. Such objects may have some hadronic states in them, for instance if the vector can decay to charged pions or if dark Higgses arise with hadronic decay modes as well. Still the hard lepton content will be much richer than usual jets, and should make them distinctive even in this case.

Finally note that ordinarily with low-energy SUSY, unless the electroweak charged states are quite light  $\lesssim 300 \text{ GeV}$ , it is not possible to probe their direct production, and instead one has to rely on cascade decays to them via the colored states. However, the presence of lepton jets in essentially all SUSY events dramatically reduces backgrounds, and should allow a probe of direct electroweak production to higher masses.

## 4. Unification, colored particles and DM production

So far we have considered the phenomenology that arises without link fields, i.e., the moose of figure 1a. We can now consider the situation with link fields as well. If we wish to assume that unification is preserved, then we should take the link fields to arise in complete GUT multiplets, including new colored states. These will allow us a new avenue of  $G_{\text{Dark}}$  production.



**Figure 4:** The simplest diagram of direct production of  $G_{\text{Dark}}$  sector. Similar diagrams exist for production of  $\tilde{D}$  and for cases where the direct production is of a link field. Such cascades generally produce additional “lepton jets”, with and without missing energy.

Of course the easiest way to have the unification unaltered “automatically” is to add states in complete multiplets of  $SU(5)$  or  $SU(3)^3/Z_3$ ; lets imagine the simplest example, where there are  $N_F$   $5 + \bar{5}$ ’s of  $SU(5)$ . These could have a mass in the neighborhood of the weak-scale by the same mechanism that makes  $\mu$  close to the weak scale. we call the states  $F^c = (D^c, L)$  and  $F = (D, L^c)$  with the obvious notation, and reserve lower-case  $q, u^c, d^c, l, e^c$  for the SM states.

The link fields could be unstable, decaying through an operator such as  $h_{\text{Dark}} D d^c$  where  $d^c$  is the usual MSSM superfield (of arbitrary flavor) and  $h_{\text{Dark}}$  is a Higgs field of  $G_{\text{Dark}}$ . This will result in a decay into hard jets and “lepton jets”, but no missing  $E_T$ . If the representations of fields under  $G_{\text{Dark}}$  are such that no renormalizeable operator can be written, it is possible that the lifetime of this could be sufficiently long that it would not decay in the event. This will be similar to the case where we identify the link fields with the dark matter, and we defer that discussion for the moment.

If we produce the superpartner of the link field,  $\tilde{D}$ , we can have decays  $\tilde{D} \rightarrow D\tilde{g}$  or  $\tilde{D} \rightarrow D\tilde{g}^*$ .  $D$  will then yield hard jets and the  $\tilde{g}$  or  $\tilde{g}^*$  will produce a SUSY cascade as described in section 3. Alternatively, we could have decays  $\tilde{D} \rightarrow D\eta_{\text{Dark}}$ , where  $\eta_{\text{Dark}}$  is a dark Higgsino/gaugino mixture, as before. This will produce the “lepton jet” from the  $\eta_{\text{Dark}}$  decay, while  $D$  will give jets plus leptons. Finally, we may have decays  $\tilde{D} \rightarrow \tilde{h}_{\text{Dark}} d^c$  and  $\tilde{D} \rightarrow h_{\text{Dark}} \tilde{d}^c$ , which may arise with comparable rates depending on the mass of the  $\tilde{d}^c$ . The former will yield “lepton jets” and missing  $E_T$  through the  $\tilde{h}_{\text{Dark}}$  cascade, while the latter will yield “lepton jets” through the  $h_{\text{Dark}}$  decay, and “lepton jets” together with missing  $E_T$  through the  $\tilde{d}^c$  via the SUSY cascade described in section 3.

It is important to note that in these cases, we achieve signatures similar to gauge mediation, augmented with “lepton jets”. However, the dark matter particle  $\chi$  is not expected to be produced in these cascades unless it has tree-level superpotential couplings to the link fields, or some singlet field that arises in some other decay.

We now consider the alternative possibility, where the link fields are also charged under  $G_\chi$ . We assume that on these fields,  $G_\chi$  acts as  $Z_2^F$ , under which  $(F, F^c) \rightarrow -(F, F^c)$ , which

keeps the lightest of these link fields stable. We will continue assume that the theory has  $Z_2^M$  matter parity for the usual reason of forbidding baryon and lepton number violation, even though this is no longer necessary to guarantee a stable DM particle, only briefly addressing the possibility on  $Z_2^M$  violation.

Even though the underlying theory only has a  $Z_2^F \times Z_2^M$  symmetry, at renormalizable level the low-energy theory has a much larger  $U(1)_L \times U(1)_D$  global symmetry acting on the link fields, which has important consequences for the phenomenology.

To begin with, note that the DM states here are identical to a ‘‘Higgsino’’; as such, there are two degenerate Majorana states, as guaranteed by the accidental  $U(1)_L$  symmetry. We have to assume that this  $U(1)_L$  is broken by higher-dimension operators too, to give the at least  $\sim 100$  KeV splitting needed to avoid having seen this DM in direct detection experiments arising from couplings to the  $Z$ -boson. For instance we need an operator of the form

$$\frac{LLH_uH_u}{M_*} \quad (4.1)$$

which gives a splitting of order  $\sim v^2/M_*$ ; such an operator can be generated by mixing with a singlet field with mass  $\sim M_*$  that could be anywhere from the TeV scale to  $\sim 10^9$  GeV.

The dark matter will easily annihilate into  $W$  bosons, depleting its relic abundance below the observed level. This provides yet another motivation for having the dark matter be part of a multiplet of states; in our picture we of course further gauge some subgroup of the global flavor symmetry rotating these states into each other. Note that for the PAMELA/ATIC signals, we need to ensure that the branching ratio for annihilating into Standard Model  $W$ 's and  $Z$ 's is less than  $\sim 10\%$ . It is easy to see that the annihilations will go into pairs of Dark gauge bosons or Standard Model gauge bosons; the ratio then scales as the ratios of  $(\alpha_{\text{Dark}}C_{\text{Dark}}/(\alpha_{\text{SM}}C_{\text{SM}})^2$  where  $C$  are the Casimirs of the corresponding representations; even for comparable gauge couplings this ratio can easily be  $\sim 10$ .

Note that if the operator of eq. (4.1) is generated by mixing with a Standard Model singlet via the Yukawa coupling  $\kappa LHS$ , then  $S$  must also be charged under the  $G_{\text{Dark}}$ , and if as is quite natural it is at the TeV scale, then the Dark Matter will be some admixture of  $L$  and  $S$ . If the invariant mass of  $S$  is smaller than that of  $L$ , the DM will be mostly a SM singlet, with an admixture  $\sim \kappa v/M$  of  $L$  after electroweak symmetry breaking. This mixing is naturally  $\sim 10\%$ , and very efficiently suppresses annihilations into SM gauge bosons down to  $\sim 10^{-4}$ . However we can get an interesting rate for annihilations into Higgses, which is controlled by the size of the Yukawa coupling  $\kappa$ .

What about the colored partners of the DM? The accidental  $U(1)_D$  symmetry guarantees that they are stable at renormalizable level. The leading higher-dimension operator that is  $Z_2^F$  invariant but breaks the two separate  $Z_2$ 's and allows the colored particles to decay is a dimension five operator

$$\int d^2\theta \frac{1}{M_G} (DL^c)(d_3^c e_3^c) \quad (4.2)$$

giving a decay width

$$\Gamma \sim \frac{M^3}{32\pi M_G^2} \sim (.1s)^{-1} \quad (4.3)$$



making for macroscopically long lifetimes that are however short enough not to cause trouble with nucleosynthesis. The collider signals of long-lived colored particles have been studied at length recently [41]; in particular the fact that a reasonable fraction of them are stuck in the detector, and decay inside it. One would naturally expect this to arise in our models. But there is a potentially dramatic addition to this signal. When the colored particle decays in the detector into its electroweak partner, it will can also radiate off  $G_{\text{Dark}}$  bosons that can promptly re-decay back into SM states. If these include  $\mu^+\mu^-$  pairs, in addition to the usual “explosion” in the detector coming from the jets in the colored particle decays, there will be muons traveling either out towards the muon chamber and/or back into the tracker!

If we don’t impose matter parity, then the new colored particles can directly couple to the SM states via for instance a superpotential term,  $\kappa q_3 L D^c$ , which would lead to a rapid decay of the colored state to the DM particle.

Whether or not the colored particle is long-lived, its presence is a boon for probing the Dark Matter sector at the LHC. Even if the colored and uncolored states start with a unified mass near the GUT scale, the colored states will become heavier by a factor of  $\sim 2$  in running down to the weak scale. But putting in the ATIC mass  $\sim 800$  GeV, this means that the colored states will have a mass near  $\sim 1.5$  TeV, perfectly accessible to be copiously produced the LHC. Furthermore, whether with a long or short lifetime, these decay dominantly directly to the DM particle and not through a complicated cascade decay process.

## 5. Discussion and outlook

As we stand on the threshold of the LHC era, astrophysical data could be giving us a first hint for what is to come. If the interpretation of [22] for PAMELA/ATIC/WMAP Haze/EGRET/INTEGRAL/DAMA is correct, a host of signals are to be expected in further astrophysical measurements, beginning with GLAST/FERMI. As we have argued here, there are also a number of possible signals at the LHC.

The new dark sector is an example of a “Hidden Valley”, but one whose properties are motivated and strongly constrained by astrophysical Data. The unique feature of the “Hidden Valleys” that are motivated by these astrophysical clues is that they have cascades that end with many leptons, rather than hadronic states. These “lepton jets” are the key LHC feature of most any supersymmetric realization of the theory of dark matter proposed in [22], in which the dark matter states transform under a gauge symmetry  $G_{\text{Dark}}$  broken at the GeV scale.

At the same time, in very natural extensions of these theories, where the dark matter or other fields in the theory transform under *both*  $G_{\text{SM}}$  and  $G_{\text{Dark}}$ , the requirement of unification promises the possibility of new colored states, some of which can be long lived. Prompt decays of new colored states or superpartners of long-lived colored states can yield topologies with and without missing energy, and with or without “lepton jets”.

These theories have a rich collider phenomenology, whose complete analysis would take us well beyond the simple discussion we have given here. It is also worth noting that the dark matter considerations have led us to consider light states in the neighborhood of  $\sim$  GeV, such particles have been considered purely from a particle physics perspective in

the past number of years, for instance, for the purposes of “hiding” the Higgs from LEP searches [42]. An intriguing connection can also be imagined with the 3 strange events observed in the Hyper-CP experiment [43], that could be interpreted as a resonance with a mass just above  $2m_\mu$  decaying to a pair of muons. And we repeat that it would be interesting to search for these light gauge bosons in existing B-factory data, as well as in possible Super-B factories.

In this short note, we have only sketched the simplest embedding of the dark matter framework proposed in [22] into a more complete supersymmetric picture of physics beyond the standard model. We leave the important task of constructing a specific model to future work. However, the sketch suffices to show that the essential ideas of [22] are (A) reinforced by a SUSY embedding, which can naturally explain the origin of the lighter GeV dark symmetry breaking scale, and (B) give rise to dramatic new signals for the LHC, and the possibility of a direct experimental probe into the rich dynamics of the Dark Sector. It is now fortunately only a short time before these ideas are decisively tested experimentally on all fronts.

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## References

- [1] O. Adriani et al., *Observation of an anomalous positron abundance in the cosmic radiation*, arXiv:0810.4995.
- [2] HEAT collaboration, S.W. Barwick et al., *Measurements of the cosmic-ray positron fraction from 1 GeV to 50 GeV*, *Astrophys. J.* **482** (1997) L191 [astro-ph/9703192].
- [3] S. Coutu et al., *Cosmic-ray positrons: are there primary sources?*, *Astropart. Phys.* **11** (1999) 429 [astro-ph/9902162].
- [4] AMS-01 collaboration, M. Aguilar et al., *Cosmic-ray positron fraction measurement from 1-GeV to 30 GeV with AMS-01*, *Phys. Lett.* **B 646** (2007) 145 [astro-ph/0703154].
- [5] J. Chang et al., *An Excess Of Cosmic Ray Electrons At Energies Of 300.800 Gev*, *Nature* **456** (2008) 362.
- [6] D.P. Finkbeiner, *Microwave ISM emission observed by WMAP*, *Astrophys. J.* **614** (2004) 186 [astro-ph/0311547].
- [7] G. Dobler and D.P. Finkbeiner, *Extended anomalous foreground emission in the WMAP 3-year data*, *Astrophys. J.* **680** (2008) 1222 [arXiv:0712.1038].

- [8] D.P. Finkbeiner, *WMAP microwave emission interpreted as dark matter annihilation in the inner Galaxy*, [astro-ph/0409027](#).
- [9] D. Hooper, D.P. Finkbeiner and G. Dobler, *Evidence of dark matter annihilations in the WMAP haze*, *Phys. Rev. D* **76** (2007) 083012 [[arXiv:0705.3655](#)].
- [10] E. Churazov, R. Sunyaev, S. Sazonov, M. Revnivtsev and D. Varshalovich, *Positron annihilation spectrum from the Galactic Center region observed by SPI/INTEGRAL*, *Mon. Not. Roy. Astron. Soc.* **357** (2005) 1377 [[astro-ph/0411351](#)].
- [11] G. Weidenspointner et al., *The sky distribution of positronium annihilation continuum emission measured with SPI/INTEGRAL*, [astro-ph/0601673](#).
- [12] G. Weidenspointner et al., *The sky distribution of 511 keV positron annihilation line emission as measured with INTEGRAL/SPI*, [astro-ph/0702621](#).
- [13] D.P. Finkbeiner and N. Weiner, *Exciting dark matter and the INTEGRAL/SPI 511 keV signal*, *Phys. Rev. D* **76** (2007) 083519 [[astro-ph/0702587](#)].
- [14] DAMA collaboration, R. Bernabei et al., *First results from DAMA/LIBRA and the combined results with DAMA/NaI*, *Eur. Phys. J. C* **56** (2008) 333 [[arXiv:0804.2741](#)].
- [15] D. Tucker-Smith and N. Weiner, *Inelastic dark matter*, *Phys. Rev. D* **64** (2001) 043502 [[hep-ph/0101138](#)].
- [16] D. Tucker-Smith and N. Weiner, *The status of inelastic dark matter*, *Phys. Rev. D* **72** (2005) 063509 [[hep-ph/0402065](#)].
- [17] S. Chang, G.D. Kribs, D. Tucker-Smith and N. Weiner, *Inelastic dark matter in light of DAMA/LIBRA*, [arXiv:0807.2250](#).
- [18] F.A. Aharonian, A.M. Atoyan and H.J. Voelk, *High energy electrons and positrons in cosmic rays as an indicator of the existence of a nearby cosmic tevatron*, *Astron. Astrophys.* **294** (1995) L41.
- [19] I. Cholis, L. Goodenough, D. Hooper, M. Simet and N. Weiner, *High energy positrons from annihilating dark matter*, [arXiv:0809.1683](#).
- [20] M. Cirelli and A. Strumia, *Minimal dark matter predictions and the PAMELA positron excess*, [arXiv:0808.3867](#).
- [21] M. Cirelli, M. Kadastik, M. Raidal and A. Strumia, *Model-independent implications of the  $e^+$ ,  $e^-$  anti-proton cosmic ray spectra on properties of Dark Matter*, [arXiv:0809.2409](#).
- [22] N. Arkani-Hamed, D.P. Finkbeiner, T. Slatyer and N. Weiner, *A theory of dark matter*, [arXiv:0810.0713](#).
- [23] I. Cholis, L. Goodenough and N. Weiner, *High energy positrons and the WMAP haze from exciting dark matter*, [arXiv:0802.2922](#).
- [24] I. Cholis, D.P. Finkbeiner, L. Goodenough and N. Weiner, *The PAMELA positron excess from annihilations into a light boson*, [arXiv:0810.5344](#).
- [25] I. Cholis, G. Dobler, D. Finkbeiner, L. Goodenough and N. Weiner, *The Case for a 700+ GeV WIMP: Cosmic Ray Spectra from ATIC and PAMELA*, [arXiv:0811.3641](#).
- [26] B. Holdom, *Two U(1)'s and epsilon charge shifts*, *Phys. Lett. B* **166** (1986) 196.

- [27] R. Foot and R.R. Volkas, *Neutrino physics and the mirror world: how exact parity symmetry explains the solar neutrino deficit, the atmospheric neutrino anomaly and the LSND experiment*, *Phys. Rev. D* **52** (1995) 6595 [[hep-ph/9505359](#)].
- [28] M. Pospelov, A. Ritz and M.B. Voloshin, *Secluded WIMP dark matter*, *Phys. Lett. B* **662** (2008) 53 [[arXiv:0711.4866](#)].
- [29] C. Boehm and P. Fayet, *Scalar dark matter candidates*, *Nucl. Phys. B* **683** (2004) 219 [[hep-ph/0305261](#)].
- [30] C. Boehm, P. Fayet and J. Silk, *Light and heavy dark matter particles*, *Phys. Rev. D* **69** (2004) 101302 [[hep-ph/0311143](#)].
- [31] J.L. Feng and J. Kumar, *The WIMPless miracle*, [arXiv:0803.4196](#).
- [32] D. Hooper and K.M. Zurek, *Natural supersymmetric model with MeV dark matter*, *Phys. Rev. D* **77** (2008) 087302 [[arXiv:0801.3686](#)].
- [33] M. Dine and A.E. Nelson, *Dynamical supersymmetry breaking at low-energies*, *Phys. Rev. D* **48** (1993) 1277 [[hep-ph/9303230](#)].
- [34] D.P. Finkbeiner, N. Padmanabhan and N. Weiner, *CMB and 21 cm signals for dark matter with a long-lived excited state*, [arXiv:0805.3531](#).
- [35] N. Borodatchenkova, D. Choudhury and M. Drees, *Probing MeV dark matter at low-energy  $e^+e^-$  colliders*, *Phys. Rev. Lett.* **96** (2006) 141802 [[hep-ph/0510147](#)].
- [36] M.J. Strassler and K.M. Zurek, *Echoes of a hidden valley at hadron colliders*, *Phys. Lett. B* **651** (2007) 374 [[hep-ph/0604261](#)].
- [37] M.J. Strassler and K.M. Zurek, *Discovering the Higgs through highly-displaced vertices*, *Phys. Lett. B* **661** (2008) 263 [[hep-ph/0605193](#)].
- [38] M.J. Strassler, *Possible effects of a hidden valley on supersymmetric phenomenology*, [hep-ph/0607160](#).
- [39] T. Han, Z. Si, K.M. Zurek and M.J. Strassler, *Phenomenology of hidden valleys at hadron colliders*, *JHEP* **07** (2008) 008 [[arXiv:0712.2041](#)].
- [40] M.J. Strassler, *On the phenomenology of hidden valleys with heavy flavor*, [arXiv:0806.2385](#).
- [41] A. Arvanitaki, S. Dimopoulos, A. Pierce, S. Rajendran and J.G. Wacker, *Stopping gluinos*, *Phys. Rev. D* **76** (2007) 055007 [[hep-ph/0506242](#)].
- [42] S. Chang, R. Dermisek, J.F. Gunion and N. Weiner, *Nonstandard higgs boson decays*, *Ann. Rev. Nucl. Part. Sci.* **58** (2008) 75 [[arXiv:0801.4554](#)].
- [43] HYPERCP collaboration, H. Park et al., *Evidence for the decay  $\Sigma^+ \rightarrow p\mu^+\mu^-$* , *Phys. Rev. Lett.* **94** (2005) 021801 [[hep-ex/0501014](#)].
- [44] J. Hisano, S. Matsumoto, M.M. Nojiri and O. Saito, *Non-perturbative effect on dark matter annihilation and gamma ray signature from galactic center*, *Phys. Rev. D* **71** (2005) 063528 [[hep-ph/0412403](#)].
- [45] J. Hisano, S. Matsumoto, M. Nagai, O. Saito and M. Senami, *Non-perturbative effect on thermal relic abundance of dark matter*, *Phys. Lett. B* **646** (2007) 34 [[hep-ph/0610249](#)].
- [46] M. Cirelli, A. Strumia and M. Tamburini, *Cosmology and astrophysics of minimal dark matter*, *Nucl. Phys. B* **787** (2007) 152 [[arXiv:0706.4071](#)].