A simplified model for dark matter interacting primarily with gluons

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ABSTRACT: We consider a simple renormalizable model providing a UV completion for dark matter whose interactions with the Standard Model are primarily via the gluons. The model consists of scalar dark matter interacting with scalar colored mediator particles. A novel feature is the fact that (in contrast to more typical models containing dark matter whose interactions are mediated via colored scalars) the colored scalars typically decay into multi-quark final states, with no associated missing energy. We construct this class of models and examine associated phenomena related to dark matter annihilation, scattering with nuclei, and production at colliders.

Contents

1 Introduction

Evidence from astrophysics and cosmology points overwhelmingly to the fact that the Universe contains a large quantity of non-relativistic matter that is at most weakly interacting [1]. Determining the identity of this dark matter (DM) is of paramount importance to our understanding of particle physics, and may offer clues as to the organizing principles that underpin the Standard Model (SM) of particle physics and its extensions.

There are two broad strategies to make progress in understanding the nature of dark matter. Specific theories such as supersymmetric extensions of the SM often contain candidate particles which could play the role of dark matter, despite their primary motivation arising from the desire to explain other mysteries. The study of such theories has the virtue that it represents exploration of the vision for dark matter contained within our best guesses for physics beyond the Standard Model. Another line of exploration seeks the more modest goal of describing the properties of dark matter while remaining agnostic about its connection to more fundamental questions. The study of such "simplified models" [2] thus sets out to do less but has the feature that it covers a wider range of the possible theory space for models of dark matter. Specific modules containing the dark matter and a mediating particle which lead to dark matter coupling to quarks [3–13] and leptons [14–16] have been constructed and investigated, as well as the universal effective field theory limit that results when the mediating particles are very heavy compared to the energies of interest [4, 17–22].

Models where the interactions with gluons dominate are slightly more subtle. $\mathrm{SU(3)}_C$ gauge invariance demands that couplings of gluons to the dark sector are effectively non-renormalizable interactions mediated by loops of colored particles. Nonetheless, such models are interesting and provide a blueprint for theories which are best tested in direct searches and high energy hadron colliders while largely escaping from indirect searches. They are a worthwhile corner of dark matter model-space to explore. Existing proposals for simplified models with this feature can be classified in three different classes: a) the mediating particle is a vector which interacts with the SM particles via effective vertices [23], b) the mediator is a (pseudo-)scalar which may or may not mix with the SM Higgs [24–28] and the dark matter is a SM singlet, c) mediator is the Higgs itself, the dark matter being charged under the electroweak $\mathrm{SU(2)} \times \mathrm{U(1)}$ [29, 30]. While all the options are theoretically well motivated, the options where the mediator is a pseudo-scalar or a Higgs, both capture features found in the minimal supersymmetric standard model.

An alternative possibility presents itself when the dark matter is a scalar particle. In that case, a quartic interaction with any other scalar in the theory is always gauge invariant and will not mediate dark matter decay. If the second (mediator) scalar is colored, it will induce coupling between a pair of dark matter scalars and gluons at one loop, represented as the dimension six interaction,

$$\frac{\alpha_s}{M^2} \, |\chi|^2 \, G^{a\mu\nu} G^a_{\mu\nu} \tag{1.1}$$

(also known as C5 [22]) when the mediating colored scalar is heavy compared to energies of interest. In this article, we explore this simplified model, examining the rich collider and astrophysical signatures of such a construction for a variety of color representations of the scalar mediator.

Our work is organized as follows. In section 2, we present the Lagrangian and couplings of the dark matter and mediator to each other and with the SM. In section 3 we compute the annihilation cross section and find the range of parameters for which the dark matter would saturate the observed density of dark matter in the Universe as a thermal relic. In section 4, we find the constraints from direct detection searches for dark matter and in section 5 discuss the constraints from collider searches. We conclude in section 6.

2 Simplified model

The basic module consists of a massive scalar (assumed complex for simplicity, though the modification to a real field is simple) χ that is a gauge singlet to play the role of dark matter, and a set of massive (typically complex) colored scalars ϕ (in representation r of $\mathrm{SU(3)}_C$) to act as the mediator with the SM. These basic pieces are described by the Lagrangian,

$$\mathcal{L} \supset \partial_\mu \chi^* \partial^\mu \chi - m_\chi^2 |\chi|^2 + (D_\mu \phi)^\dagger D^\mu \phi - m_\phi^2 |\phi|^2 \tag{2.1}$$

where $D_\mu \phi$ is a covariant derivative that includes interactions with the electroweak gauge fields (in cases where ϕ is charged under $\mathrm{SU(2)} \times \mathrm{U(1)}$) and coupling to the gluons G^a_μ:

$$D_\mu \phi \equiv \partial_\mu \phi - i g_s \frac{\lambda^a_r}{2} G^a_\mu \phi + \text{ Electroweak} \tag{2.2}$$

where g_s is the strong coupling and $\lambda_r^a/2$ are the generators of $\mathrm{SU}(3)_C$ in representation r. As discussed below, for specific color representations r it is well-motivated to consider a set of fields ϕ_i labeled by a flavor index i.

The dark matter interacts with the mediator via a quartic interaction,

$$\lambda_d \, |\chi|^2 |\phi|^2 \,. \tag{2.3}$$

It is interesting to note that this interaction allows for χ to be charged under a Z_2 symmetry forcing it to be stable, though ϕ can either be Z_2-charged or not. This feature, and the freedom to choose the color representation of ϕ somewhat arbitrarily result in drastically different phenomenology compared to the usual simplified models in which dark matter interacts with a colored mediator [5–8]. The symmetries also permit additional quartic interactions such as,

$$\lambda_{\chi h}|H|^2|\chi|^2 + \lambda_{sh}|H|^2|\phi|^2 \,, \tag{2.4}$$

where H is the SM Higgs doublet. The former leads to Higgs portal couplings for the dark matter [31], and has been well-explored in the literature. While such a coupling is inevitable, we assume that its effects are sub-dominant to λ_d for the purposes of our discussion. The latter term will shift the ϕ mass after electroweak symmetry-breaking, and induces couplings between the ϕ and the Higgs boson. Such a coupling can be constrained by the shift it induces in the effective coupling of the SM Higgs boson to gluons [32]. In principle it is also expected to be generically present, but we shall consider the case where it is also small and thus unimportant.

2.1 Interactions of the mediator with quarks

In general, the mediators can interact with quarks, allowing them to decay into hadrons. That such decays happen is important to insure that a primordial population of ϕ do not (being colored) bind with nuclei, which would be subject to strong constraints from searches for anomalously heavy isotopes [33]. For $\mathrm{SU}(3)_C$ representations $r = 3, 6, 8$, interactions with a pair of quarks/anti-quarks are permitted at the renormalizable level, provided the $\mathrm{SU}(2) \times \mathrm{U}(1)$ charges of ϕ are also chosen appropriately. The possibilities were tabulated in ref. [32], which assigns flavor indices to the ϕ fields such that the coupling to quarks can be governed by the principle of minimal flavor violation (MFV) [34, 35]. MFV dictates that all breaking of the $\mathrm{SU}(3)_{Q_L} \times \mathrm{SU}(3)_{u_R} \times \mathrm{SU}(3)_{d_R}$ flavor symmetries of the (massless) SM be proportional to the SM Yukawa interaction matrices Y_u and Y_d, and is motivated to control what would otherwise be very large contributions to flavor-violating observables in the quark sector which would be in conflict with precision measurements.

For higher color representations, coupling to quarks is still permitted but must be represented as non-renormalizable interactions, implying the existence of additional heavy particles.

We concentrate on the specific case of a color triplet ϕ which has electroweak quantum numbers such that it can interact with a pair of right-handed up-type quarks, though we will comment on other cases where appropriate. A ϕ that is a color triplet with charge

−4/3 can couple to $u_i u_j$ provided that the color indices are contracted anti-symmetrically. MFV is implemented by choosing ϕ to have its own $SU(3)_{u_R}$ flavor index, and a flavor singlet is constructed by contracting the flavor indices anti-symmetrically, $\epsilon_{ijk}\phi_i u_j u_k$. This type of scalar "diquark" bears some resemblance to the squarks of an R-parity-violating supersymmetric theory. However, their weak charges and the flavor structure of their couplings are distinct from the supersymmetric case.

Consistently with MFV, the large top Yukawa coupling allows for deviations of coupling of ϕ_3 from $\phi_{1,2}$. If one neglects small corrections proportional to the up and charm-quark masses, the resulting terms in the Lagrangian are,

$$y_1 \ (\phi_1 c_R - \phi_2 u_R)\, t_R + y_2 \ \phi_3 u_R c_R + h.c \qquad (2.5)$$

where u_R, c_R, and t_R are Weyl spinors corresponding to the (right-handed parts of the) quark mass eigenstates, y_1 and y_2 are complex dimensionless parameters, and color indices are implicit (contracted anti symmetrically). The same corrections from the top Yukawa can result in large splitting between the masses of ϕ_1 and ϕ_2 (which are themselves expected to be degenerate in the limit where the up- and charm-quark masses are neglected) and the mass of ϕ_3.

In summary, when ϕ is a color triplet which couples to a pair of up-type quarks, MFV suggests it is a flavor triplet under $SU(3)_{u_R}$. The theory is described by two dimensionless couplings and two masses,

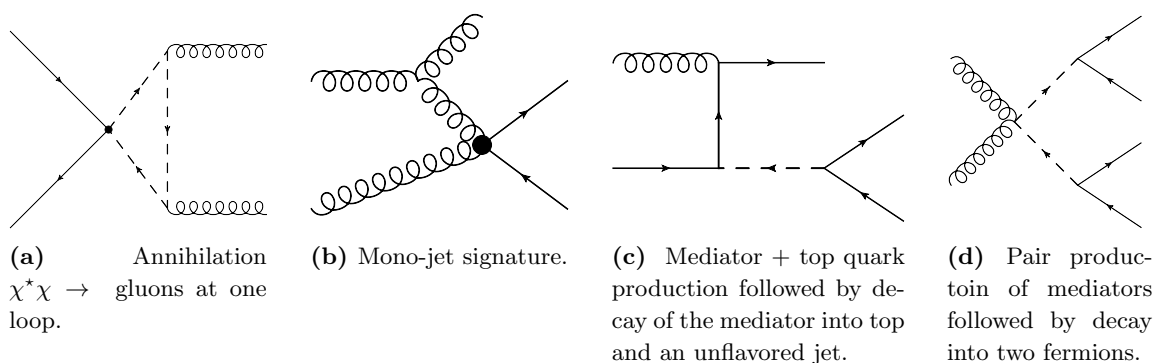$$\{y_1, \ \ y_2, \ \ m_{\phi_1}, \ \ m_{\phi_3}\}, \qquad (2.6)$$

where m_{ϕ_1} is the (approximately degenerate) masses of the two colored scalars which couple to $u_R t_R$ and $c_R t_R$ with (approximately equal) coupling y_1 and m_{ϕ_3} is the mass of the third scalar with couples to $u_R c_R$ with coupling y_2.

3 Annihilation cross section

The cross section for the dark matter to annihilate is the primary quantity determining the prospects for observing it via indirect detection methods, and also determining its relic density, if one assumes a standard cosmological ΛCDM history. While we are agnostic toward the actual mechanism responsible for producing χ in the early Universe, the relic density singles out a particularly interesting region of parameter space.

The primary mechanism for annihilation depends very sensitively on whether the mediators are heavier or lighter than the dark matter itself. When one or more of the mediators are lighter, the annihilation will be dominated by the tree level process $\chi\chi^* \to \phi\phi^*$ (where the ϕ eventually decay into quarks). This rate is entirely controlled by the quartic coupling λ_d, with rather mild dependence on the mass of ϕ,

$$\langle \sigma v_\chi \rangle = \frac{\lambda_d^2 \times r}{64\pi m_\chi^2} \sum_{m_{\phi_i} < m_\chi} \sqrt{1 - \frac{m_{\phi_i}^2}{m_\chi^2}} \qquad (3.1)$$

(a) Annihilation $\chi^{\star}\chi \rightarrow$ gluons at one loop.

(b) Mono-jet signature.

(c) Mediator + top quark production followed by decay of the mediator into top and an unflavored jet.

(d) Pair production of mediators followed by decay into two fermions.

Figure 1. Representative Feynman diagrams for various processes involving the mediating colored-scalar that we will explore.

where r is the color representation of ϕ and the sum includes all flavors of ϕ whose masses are less than m_χ.

When all of the mediators have masses larger than m_χ, annihilation can go through off-shell ϕ's into quarks (depending on the strength of the coupling of the ϕ particles to the quarks), into Higgs bosons through the $\lambda_{\chi h}$ coupling, or into gluons through a loop of ϕ particles (see figure 1a). The former two processes can be neglected when $\lambda_{\chi h}$ and the y_i couplings are very small, but the one loop coupling to gluons is also proportional to λ_d. The resultant $\chi\chi^* \rightarrow gg$ cross section can be expressed in the non-relativistic limit,

$$\langle \sigma v_\chi \rangle = \frac{\lambda_d^2 \, T_r^2 \, \alpha_s^2}{64\pi^3 m_\chi^2} \left| \sum_i \ \left(1 + 2m_{\phi_i}^2 C_0\right) \right|^2 \tag{3.2}$$

where C_0 is the usual scalar three-point integral [36] with arguments $C_0(0, 0, 4m_\chi^2; m_{\phi_i}, m_{\phi_i}, m_{\phi_i})$, T_r is the Casimir for representation r of SU(3), and $\alpha_s \sim 0.1$ is the strong coupling constant.

For a thermal relic in a standard ΛCDM cosmology, the annihilation cross section should be approximately $\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{cm}^3\text{s}^{-1}$ (with a relatively mild dependence on m_χ becoming more pronounced for small masses) [37]. Given the loop suppression, it is very difficult to realize this cross section for all of the $m_\phi > m_\chi$ apart from a narrow sliver around $m_\phi \lesssim 1000 \,\text{GeV}$. In this region, a thermal relic requires one to invoke large coupling to quarks y_i or the Higgs $\lambda_{\chi h}$ to allow the other channels to make up the difference in the cross section. For $m_\chi > m_\phi$, one can realize a thermal relic for a wide variety of masses and couplings λ_d. Our results are presented in figure 2.

4   Scattering with nuclei

Direct searches for dark matter are most sensitive to its scattering with heavy nuclei. The most stringent constraints are on spin-independent (SI) interactions with nucleons, which are typically coherent for the momentum transfer of interest to typical experiments ($\sim 10 \,\text{MeV}$). Given the large expectation value of matrix elements for gluons in the nucleon,
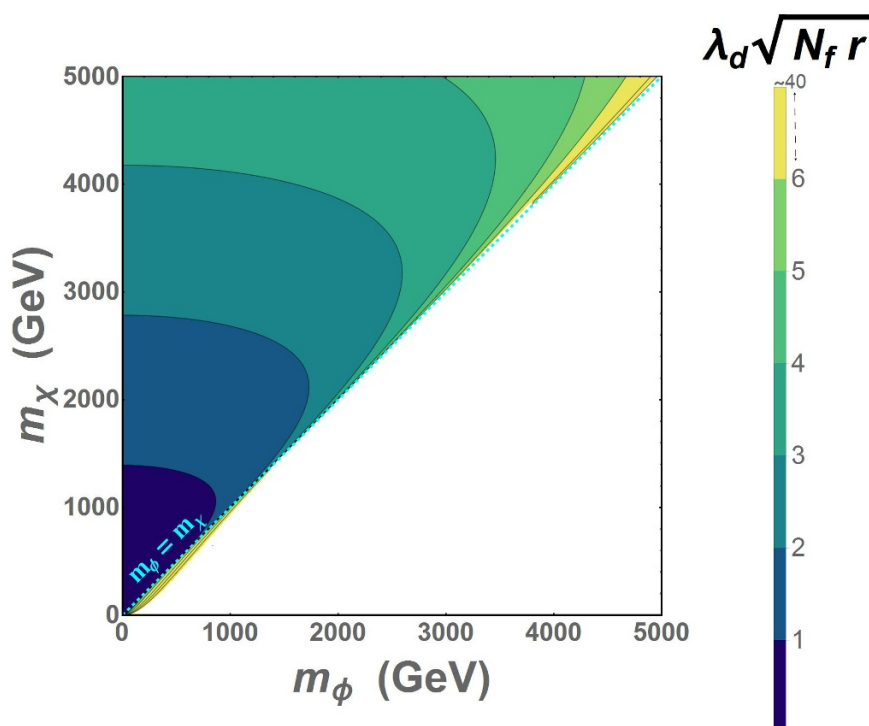
Figure 2. The product of quartic interaction λ_d with the square root of product of r dimensional color representation of ϕ and N_f number of flavors with mass less than m_χ, required to saturate the observed dark matter density as a thermal relic, are represented as colored contours in the plane of m_ϕ-m_χ. Almost all the parameter space where $m_\phi < m_\chi$ is compatible with a thermal relic density. Where $m_\phi > m_\chi$, the DM annihilation proceeds via loops and, only a small region of parameter space is allowed without including any additional couplings.

the dominant contribution will be from the effective coupling to gluons induced by loops of the mediators (cf. figure 1a).

To good approximation, the coupling to gluons can be represented by its leading term in the expansion of the momentum transfer divided by the mediator mass. In this limit, the effective coupling can be represented by the operator C5,

$$\frac{\lambda_d \alpha_s T_r}{48\pi} \sum_i \frac{1}{m_{\phi_i}^2} |\chi|^2 G_{\mu\nu}^a G^{a\mu\nu}, \tag{4.1}$$

whose coefficient is determined by λ_d, T_r, and the masses of the mediators. It is convenient to introduce the masses added in parallel,

$$\frac{1}{\overline{m}^2} \equiv \sum_i \frac{1}{m_{\phi_i}^2}, \tag{4.2}$$

which in the limit where all mediators have equal masses is $1/\overline{m}^2 \to N_f/m_\phi^2$. Combined
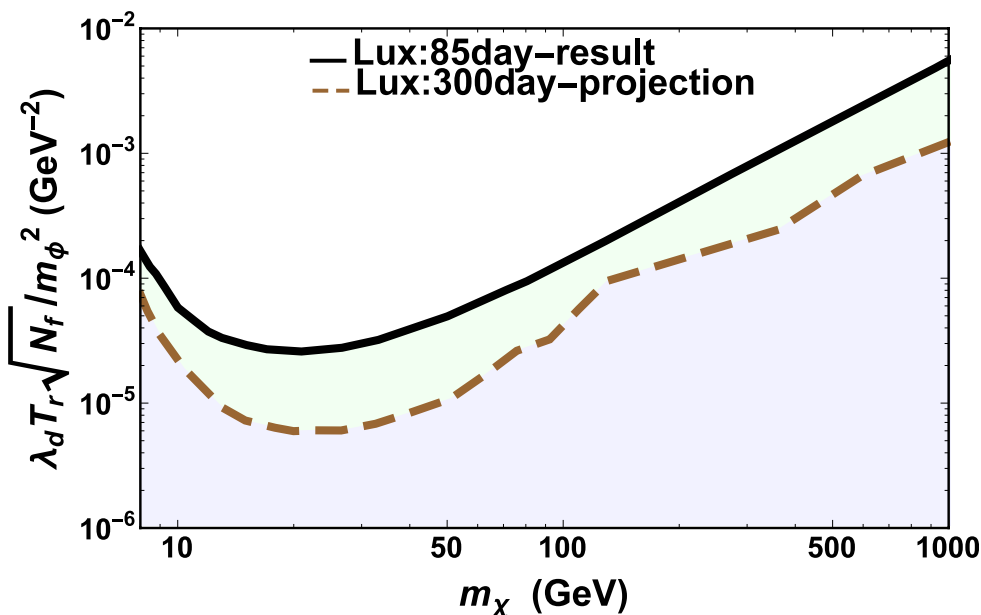
Figure 3. Current (solid line) and projected (dashed line) bounds on $\sum \lambda_d T_r \sqrt{N_f}/m_\phi^2$ based on searches for dark matter-Xenon scattering by LUX. The region above the solid line is excluded.

with the gluonic matrix elements, the result is a spin-independent cross section σ_{SI},

$$5.2 \times 10^{-44} \text{cm}^2 \, (\lambda_d T_r)^2 \Big(\frac{\mu_\chi \, m_\chi}{10 \, \text{GeV}^2} \Big) \Big(\frac{200 \, \text{GeV}}{\overline{m}} \Big)^4 , \tag{4.3}$$

where μ_χ is the reduced mass of the nucleon - dark matter system. Through the renormalization group the gluon operator will mix with the scalar quark bilinear, and is expected to lead to modest changes to this expectation which grow as the log of m_ϕ [38].

Currently, the most stringent bound on σ_{SI} for a wide range of dark matter mass is obtained from the null observation after 85 days of live running by the LUX experiment with a liquid Xenon target [39]. In figure 3, we show the bounds on $\lambda_d T_r/\overline{m}^2$ as a function of dark matter mass derived from those bounds, and also compare with projected bounds based on 300 days of live running. For $\lambda_d T_r \sqrt{N_f} \sim 1$, mediator masses of order $200 \, \text{GeV}$ remain consistent with observations.

5   Collider constraints

With an effective coupling to gluons and additional heavy colored states, this simplified model leads to rich phenomenology at hadron colliders such as the LHC. Since the mediating scalars do not themselves decay into the dark matter, the associated phenomenology is quite distinct from the usual R-parity conserving SUSY, with the specific details dependent on the choice of color representation r as well as the transformation under the quark flavor symmetries of the mediators.

5.1 Missing energy signature

Independent from the choices of r and flavor embedding, the effective coupling to gluons allows production of pairs of dark matter. When accompanied by additional radiation in the form of quarks or gluons (see figure 1b), the presence of the dark matter can be inferred by the imbalance of transverse momentum, resulting in a mono-jet signature.

In the limit in which the energies of the participating partons are all much smaller than m_ϕ, the dominant interaction can be represented as the contact interaction C5, much as was the case describing the scattering with nuclei. For this region of parameter space, the bounds from ATLAS and CMS [40, 41] apply and (translated from Dirac dark matter to complex scalars) provide a limit on the same combination of m_ϕ and λ_d. The most stringent limit is currently from CMS [40], and requires,

$$\frac{\lambda_d T_r}{48\pi}\,\frac{1}{\overline{m}^2} \le \frac{1}{(207\text{ GeV})^2} \tag{5.1}$$

for $m_\chi \lesssim 200\,\text{GeV}$, with the limit weakening to nonexistent as the dark matter mass approaches $\sim 1\,\text{TeV}$.

These limits are only reliable for mediator masses well above the typical momentum transfer in the events, characterized for the CMS analysis by the cut on missing transverse momentum of $E_T^{\text{miss}} > 500$ GeV. For small r and numbers of mediators, there is essentially no useful bound from the mono-jet search for any perturbative value of λ_d. Only for very large values of r, N_f, and/or λ_d are there meaningful bounds.

In the regime of smaller m_ϕ, the effective contact interaction softens, driving the signal to look more like background. While a detailed study is beyond our scope, it is unlikely that the bounds are strong enough to be useful in this part of the parameter space. Additionally, bounds obtained in this section are comparable to a detailed analysis of missing energy signature, for an axial vector mediator along with a fermionic dark matter candidate, which obtains a lower bound on the mass of the mediator of the order ~ 1 TeV for $m_\chi \sim 100$ GeV with order 1 couplings and the mediator mass is unconstrained for $m_\chi > 300$ GeV [42].

5.2 Production of the colored mediators

The mediating scalars interact directly with gluons, and as a result have large pair production cross sections which to good approximation are functions only of r and the mass of the mediator. As outlined above, they typically decay into two or more jets of hadrons, which may favor certain flavors (depending on the how the weak charges and transformation under the quark flavor symmetries are chosen). Such searches are notoriously difficult, with null searches for pair production of a pair of color triplet resonances decaying into two-jets excluding masses below about 350 GeV [43]. For larger r and/or more complicated transformation under the flavor symmetries, more exotic configurations of a pair of resonances each decaying to a large multiplicity of jets are possible. While such events have spectacular kinematic structure, revealing its existence is complicated by large combinatoric backgrounds. We leave the exploration of such novel signatures for future work.

In the limit in which the coupling to quarks are extremely tiny, the mediators may be long-lived on collider scales, and the best bounds come from searches for colored particles
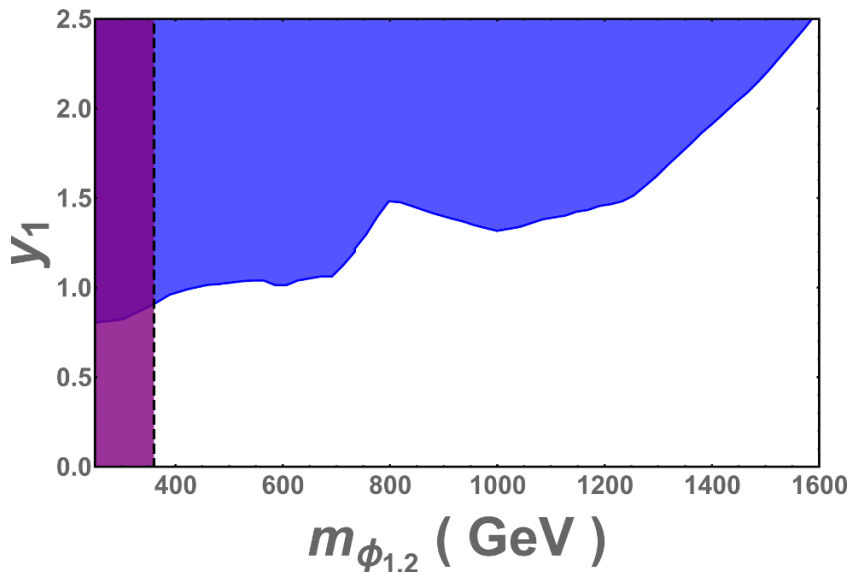
Figure 4. Excluded region of the plane of $m_{\phi_{1,2}}$ and y_1 from searches for anomalously large production of $t\bar{t}$ + one jet (solid blue region) and $t\bar{t}$ + two jets (purple shaded region).

stopping in the detector material, and then later decaying "out of time". Searches for such objects which are colored triplets or octets result in bounds on their masses of roughly $m \geq 900$ and $m \geq 1200\,\text{GeV}$, respectively [44, 45].

5.3 Color triplet mediator coupled to $u_R u_R$

For our specific example of a color triplet mediator coupled to a pair of right-handed up-type quarks, there are three mediators, $\phi_{1,2,3}$ which couple to $c_R t_R$, $u_R t_R$, and u_R, c_R, respectively. Since ϕ_3 decays into unflavored jets of hadrons, the CMS bound [43] on pairs of dijet resonances (see figure 1d) requires $m_{\phi_3} \geq 350\,\text{GeV}$. For large enough y_2, there are bounds coming from searches for resonances in dijet events. The bounds are a somewhat complicated collection of searches at different collider energies (for a nice review, see [46]). The most constraining searches [47–50] typically require y_2 less than about 0.8, with the most tight constraints ($y \lesssim 0.2$) occurring for masses around 1 TeV and essentially no constraint on masses greater than about 3 TeV.

ϕ_1 and ϕ_2 have flavor-changing couplings to the top quark, together with a charm or up quark, respectively. Consequently, they decay into a top and an unflavored jet, resulting in top-rich signatures. Pair production of $\phi_{1,2}^* \phi_{1,2}$ thus leads to a $t\bar{t} + 2$ jets signature, with resonant structure in the invariant masses constructed from one of the tops and one of the unflavored jets (figure 1d). The rate of this process is controlled by QCD, and thus depends on the masses of the mediators but not the strength of their coupling to quarks. There is a dedicated CMS analysis for this kinematic structure [51], which for pair production of (two mass-degenerate) color triplet scalars requires $m_{\phi_{1,2}} \geq 350\,\text{GeV}$ for essentially any value of the coupling y_1 leading to a prompt decay. The excluded area is represented as the purple shaded region in figure 4.

In addition, for small enough masses the contribution to the inclusive $t\bar{t}$ production could be large enough to disagree with observations. For two degenerate color triplet scalars, the inclusive top cross section measurement at 8 TeV [52, 53] provides the weaker constraint $m_{\phi_{1,2}} \geq 220$ GeV, again roughly independently of the value of y_1.[1]

If the coupling to quarks is large enough, there is also the possibility of radiating a mediator from an up or charm quark, resulting in the signature of $t\bar{t}+$ unflavored jet (see figure 1c, with a resonance between one of the tops and the jet. There are dedicated searches for this kinematic structure [56, 57] which place bounds in the plane of the masses $m_{\phi_{1,2}}$ and coupling y_1. The resulting excluded region is plotted as the solid area in figure 4.

6   Conclusions

A model in which the dark matter interacts primarily with the Standard Model via the gluons (and not appreciably with the quarks) is an interesting corner of dark matter theory space, one worthy of both theoretical and experimental exploration. We construct an appealing renormalizable simplified model in which the dark matter is a scalar particle, whose coupling to gluons is induced through a quartic interaction connecting it to exotic colored scalars. A large number of choices for color and flavor representations of the scalars exist, though all share some common features. In particular, the strongest constraints (for $m_\chi \gtrsim 10$ GeV) typically come from direct searches for dark matter scattering with nuclei, with missing energy signals at the LHC strongly suppressed. The colored scalars themselves typically decay into a number of quarks, motivating searches at the LHC for multi-jet signals of resonantly produced pairs of particles with QCD-sized production cross sections.

It is perhaps surprising that some models of dark matter may manifest themselves at a hadron collider most readily through a signature *without* any missing transverse momentum.

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[1]We simulate the production cross section at leading order using `MadGraph 5` [54] and include a k-factor of 1.7 extracted from calculations of squark productions at NLO [55].

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