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A Simplified Model of Dark Matter Interacting Primarily with Gluon

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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 feature that (in contrast to more typical models containing scalar dark matter) 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. We compare the results obtained from effective field theory (EFT) with a loop-induced calculations for the collider processes and show that EFT is not applicable for a large parameter space where mediator mass is comparable to the cuts on missing energy. We calculate the bounds from from $\sqrt{s} = 8$ and 13 TeV data and show the expected reach of $\sqrt{s} = 14$ TeV LHC and 100 TeV FCC in constraining or discovering the model.

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1. Introduction

The invisible component of the observed matter, known as dark matter (DM), is now precisely measured with a number of independent astrophysical probes. It forms one of the most pressing unsolved puzzles of modern physics. In this work, we consider a model where a DM interacts primarily with the gluons [1]. This model, termed gluphilic scalar DM (GSDM) admits a singlet-scalar, stabilized by a Z_2 symmetry, as the DM candidate 'χ.' The model also includes a colored scalar 'ϕ' which mediates the interactions of χ with the Standard Model (SM) particles.

If a DM couples with the SM particles, it can be probed with direct detection experiments in its interactions with nucleons, with indirect signals from annihilation in astrophysical regions of high DM density, by verifying its compatibility with the observed relic density and at colliders via processes involving a missing energy component.

Missing transverse energy (MET) channels are an important part of the physics program at the LHC. Among the MET channels, the monojet process has the largest cross section due to the QCD coupling involved. Often, interpretations of DM searches are made in an effective field theory (EFT) framework where bounds are obtained on the scale for new physics contributions. As there is no reason a priory to believe that the new physics contributions may not come at a low energy scale, a complete calculation is necessary to fully utilize the monojet searches at hadron colliders and probe DM models.

In this study we explore the astrophysical and colliders signatures of the GSDM model.

2. The Simplified Model

The GSDM model is defined by the following renormalizable lagrangian.

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

where, χ is a scalar DM candidate which is neutral under SM charges. ϕ represents a colored scalar which transforms under the $SU(3)_C$ representation of dimension r and couples with gluon via the covariant derivative D^μ. The coupling between the DM and ϕ is represented by λ_d. In the following work, we assume for simplicity that ϕ is not charged under the $SU(2)$ weak symmetry. We call this model gluphilic as the mediating scalar induces a coupling between the DM and gluon via the following effective operator.

$$\mathscr{L}_{\text{EFT}} = \frac{\lambda_d \alpha_s T_r}{48\pi} \frac{1}{m_\phi^2} \, |\chi|^2 G^a_{\mu\nu} G^{a\mu\nu} \ , \tag{2.2}$$

3. Astrophysical Signatures

We calculate the cross-section for DM pair annihilation to ϕ pair. The colored scalar is then assumed to slowly decay to SM particles producing the correct relic density in the thermal ΛCDM cosmology. In Figure 1 constraints are obtained on the coupling λ_d, the $SU(3)$ representation of the scalar 'r' and the number of flavors of the scalar N_f. When the DM is heavier than the mediator, the thermal DM scenario is indeed viable for a large range of parameter space. However,

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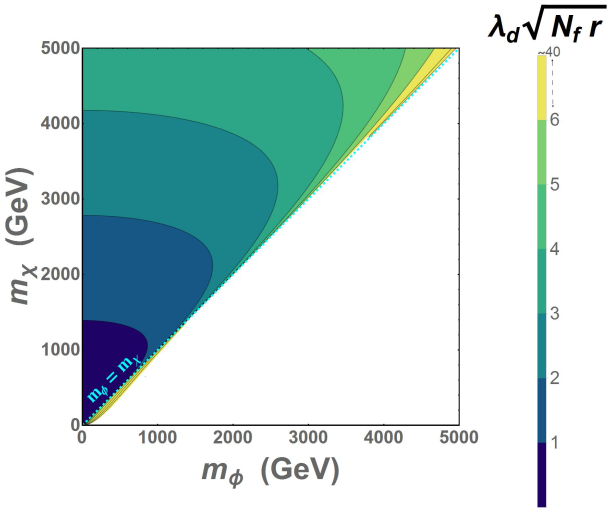


Figure 1: Parameter space of GSDM model compatible with the observed relic density in the thermal ΛCDM cosmology as a function of DM χ and mediator ϕ masses.

a light DM candidate is more interesting from the point of view of collider searches. In this case, additional couplings of the DM with Higgs or a non-thermal mechanism of DM production needs to be invoked to explain the observed relic density. A GSDM candidate would also interact with

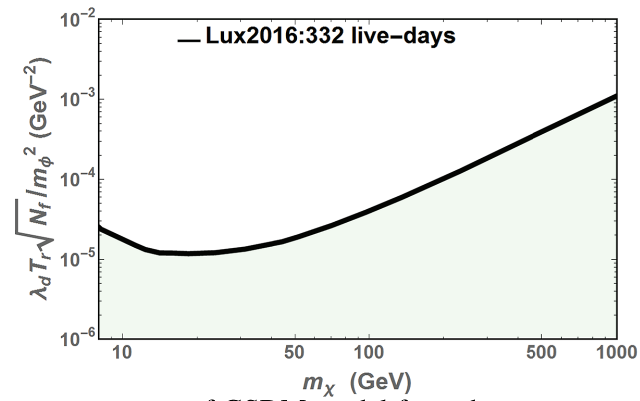
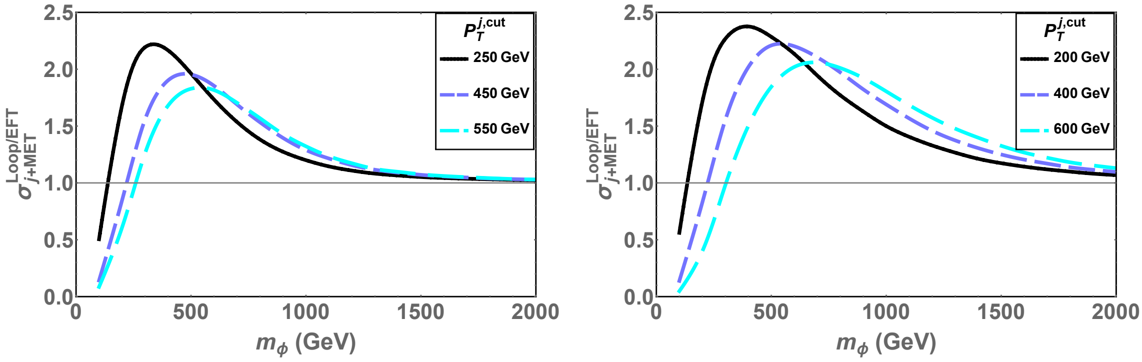


Figure 2: Constraints on parameters of GSDM model from the recent measurements at LUX detector [3] as a function of DM χ mass.

heavy nuclei and can be probed in the searches of DM at direct detection experiments. Figure 2 shows the constraints obtained on this model due to absence of any observations of DM in the recently released LUX results [3].

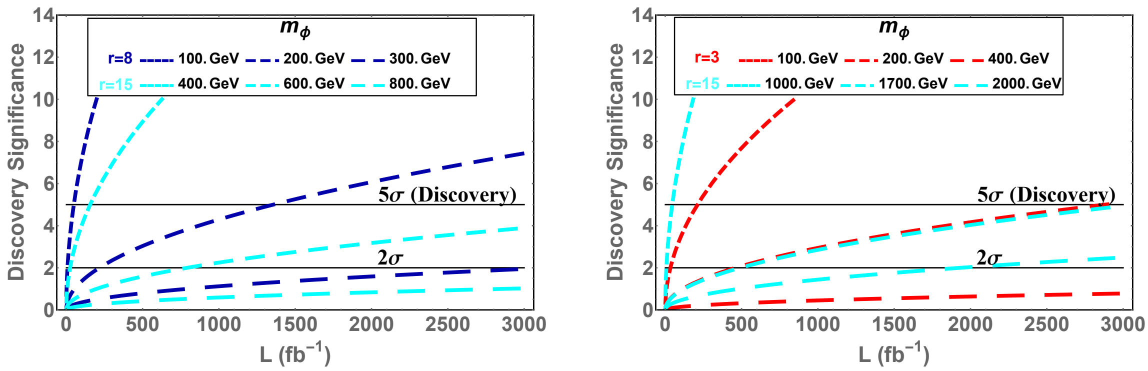
4. Missing Energy + Jet

The production of missing transverse energy in association with a single jet provides the highest cross section among the MET processes at the LHC due to the strong coupling. A common way to interpret new physics searches at colliders is to find bounds on effective operators which



(a) $\sqrt{s}=8$ TeV (b) $\sqrt{s}=13$ TeV

Figure 3: Ratio of the full calculation to the EFT approximation, as a function of m_ϕ (with other parameters fixed as described in the text), for three values of the minimum p_T^j and two choices of center of mass energy, as indicated.



(a) $\sqrt{s} = 13$ TeV LHC. (b) $\sqrt{s} = 100$ TeV FCC.

Figure 4: Reach for constraining the parameter space of GSDM at 14 TeV LHC and 100 TeV FCC is shown in the above plots of significance $S/\sqrt{S+B}$ vs luminosity. Mediators belonging to triplet (red) and octet (blue) representations of SU(3)$_C$ are shown. Jet cut of $p_T^j > 200$ GeV is assumed along-with $m_\chi = 1$ GeV and $\lambda = 1$.

contribute to the process. The bounds obtained on GSDM model from monojet process in the framework of effective operator shown in the introduction are quite weak.

$$\frac{\lambda_d T_r}{48\pi} \frac{1}{m_\phi^2} \leq \frac{1}{(207\ \mathrm{GeV})^2}. \tag{4.1}$$

Since EFT is only applicable when the mediating scale is much larger than the typical energy and jet energy cut-off scales, the above result does not represent the whole parameter space of the model. We calculate the one-loop diagrams which contribute to the monojet process using three independent methods (see [1] for details). We compare these results with those expected from the EFT and find that at the typical energy scale of the LHC the EFT underestimates the cross-section almost by a factor of two. This comparison is shown in Figure 3 for 8 and 13 TeV LHC runs.

We calculate the reach of LHC in the high luminosity limit (see Figure 4a) and also the reach of a future 100 TeV collider in probing the GSDM model (see Figure 4b). These figures show the reach for the case of the optimistic scenario from the LHC perspective where the DM is much lighter than the jet p_T cut $m_\chi \sim 10$ GeV and the coupling between DM and mediator is large, $\lambda_d = 1$. To maximize the cross-section the lowest p_T cut of 200 GeV is taken in agreement with lowest cuts at the current ATLAS and CMS searches. With 3 ab^{-1} of luminosity, LHC can probe a color triplet mediator mass up to 50 GeV and a dim-15 mediator up to 500 GeV. FCC can probe much larger masses up to TEV scale within 300 fb^{-1} luminosity.

5. Further Signatures of GSDM

In this article we have presented a UV complete model of scalar DM which is compatible with present astrophysical and collider constraints. A colored scalar can be probed in multiple channels at a collider which do not include missing energy. Most of these channels depend on the specific SU(3) representation of ϕ and the flavor symmetry imposed on its interaction with the quarks (see for example the discussion in [1]). However, a small coupling of ϕ with quarks is necessary in order to satisfy both the relic density constraints and the constraints on stable colored particles [4]. As long as such a small coupling exists ϕ can be probed in the four jets final state channel largely independent of the magnitude of this coupling. This channel constraints the mass of a color triplet scalar to $m_\phi > 510$ GeV [5]. In addition to four-jets, loop contribution from a colored scalar to the di-jet process and the running of strong coupling is also a model independent probe of the mass of ϕ. This calculation is indeed underway.

Probing DM in other MET channels beyond monojet may also be viable. In channels such as missing transverse energy + Mono-Higgs/di-Higgs/di-jet the cross-section may be lower however the background is also much smaller.

Due to the gluphilic nature, the possibility of discovering such a model at the LHC and studying it precisely at the FCC is indeed quite inviting.

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