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Mono-jet signatures of gluphilic scalar dark matter

Rohini M. Godbole [a], Gaurav Mendiratta [a,b], Ambresh Shivaji [c,d,*], Tim M.P. Tait [e]

[a] CHEP, Indian Institute of Science, Bangalore, 560012, India
[b] Salk Institute for Biological Studies, La Jolla, CA, 92037, USA
[c] INFN, Sezione di Pavia, Via A. Bassi 6, 27100 Pavia, Italy
[d] Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
[e] Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

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ABSTRACT

A gluphilic scalar dark matter (GSDM) model has recently been proposed as an interesting vision for WIMP dark matter communicating dominantly with the Standard Model via gluons. We discuss the collider signature of a hard jet recoiling against missing momentum ("mono-jet") in such a construction, whose leading contribution is at one-loop. We compare the full one-loop computation with an effective field theory (EFT) treatment, and find (as expected) that EFT does not accurately describe regions of parameter space where mass of the colored mediator particles are comparable to the experimental cuts on the missing energy. We determine bounds (for several choices of SU(3) representation of the mediator) from the $\sqrt{s} = 8$ TeV data, and show the expected reach of the $\sqrt{s} = 13$ TeV LHC and a future 100 TeV pp collider to constrain or discover GSDM models.

1. Introduction

An overwhelming body of evidence from astrophysical observations points toward a large, invisible component of the matter content of the universe, usually termed dark matter (DM). Any candidate for DM has to be stable over the lifetime of the universe, requiring either extremely small couplings with the Standard Model (SM) particles, or the presence of additional symmetries forbidding its decay. If the DM has sufficiently strong coupling to SM particles, it can be probed at high energy hadron colliders, where it typically escapes from the detectors and thus appears as an imbalance in the visible momentum. Not surprisingly, "missing transverse energy" (MET, or $\not{E}_T$) channels are an important part of the physics menu at the Large Hadron Collider (LHC) [1].

In many models of dark matter, including some of the more popular theories such as supersymmetric extensions of the SM, the processes giving rise to MET occur at tree level. Such processes include production of one or more mediator particles which decay into dark matter and/or visible radiation. In the limit in which the mediator particles are heavy, all theories flow into a universal effective field theory (EFT) consisting of non-renormalizable interactions between the dark matter and the SM [2–7]. When the mediator particles are light, and must be explicitly included in the description, these are supplanted by simplified models (see e.g. [8,9]).

However, another interesting class of theories has the dark matter communicating with the SM primarily through loop processes. This further opens new portals of interaction, such as communication with SM gluons, whose tree level interactions are strongly constrained by gauge invariance. The particle in the loop may be an SM particle, for example see [10], or a BSM particle. In [11], such a model was explored in which the dark matter (χ) is a scalar particle whose primary renormalizable interaction is through a quartic interaction with an exotic colored scalar (ϕ), leading to a one-loop coupling of two dark matter particles to gluons (see also Ref. [12] for related discussion). While simple, such a construction leads to novel features. For example, the Z_2 symmetry posited to insure that χ is stable need not act on the ϕ, which can decay into hadronic jets. Such particles can look somewhat like the squarks of an R-parity violating supersymmetric model (despite the current framework being a model of dark matter), and are rather weakly constrained by LHC searches for resonant structure in dijet and 4-jet final states [13–17] (see [11] for detailed discussion). However, it is the mono-jet process, in which a pair of dark matter recoils against a hadronic jet, which directly probes the DM and its coupling to the SM. Such a theory is a natural theoretical labo-

* Corresponding author.
E-mail address: gmendiratta@salk.edu (G. Mendiratta).

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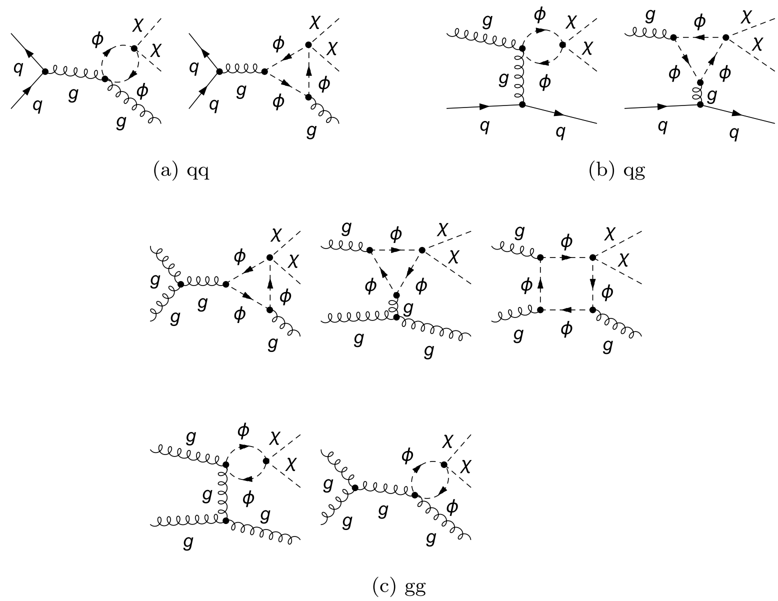

Fig. 1. Representative diagrams for the subprocesses contributing to $pp \to j\chi\chi^*$ at a hadron collider.

ratory to explore the features of a construction in which the dark matter couples to gluons through loops.

Ref. [11] confined its discussion of the mono-jet signal to the limit of heavy mediators, in which the loop diagram matches on to the operator C5 in the EFT [7]. In the current work, we extend this result to the case of lighter mediators by performing the full one-loop calculation of the mono-jet process, valid for all mediator masses. Our primary aim is to understand the current and future limits from the LHC and a future 100 TeV pp collider (such as the proposed future circular collider (FCC)) on this interesting theory of dark matter, but as a by-product we also examine the systematics of how the full theory transitions into the EFT description in the heavy mass limit.

This article is organized as follows. In section 2, we review the most important features of the gluphilic scalar dark matter (GSDM) model, and its mapping into the EFT language at large mediator masses. In section 3, we detail the loop calculation for the mono-jet process, discuss the role of gg, gq, and $q\bar{q}$ initial states, and compare the results derived from the EFT limit. In section 4, we show the bounds interpreted from current LHC 8 TeV, run-II data and the projected mono-jet cross-sections along with the expected leading order backgrounds at the LHC Run II (13 TeV) and the FCC (100 TeV). In section 5, we conclude with some outlook.

2. GDSM model and mapping to EFT

The basic module for a scalar dark matter (taken to be complex here, though the generalization to a real scalar is trivial) coupling to a colored scalar ϕ consists of renormalizable interactions:

$$\lambda_{sh} H^\dagger H \phi^\dagger \phi + \lambda_d \chi^* \chi \phi^\dagger \phi, \tag{1}$$

where H is the SM Higgs doublet. The quartic λ_{sh} implements DM coupling to the SM Higgs, and is known as the Higgs portal [18]. It leads to interesting predictions for Higgs physics which generically rule out regions of the parameter space consistent with the dark matter being a thermal relic [19]. We assume this coupling is small enough to provide subdominant effects in our analyses below. In that limit, the parameters are the coupling λ_d, the masses of ϕ and χ, and the choice of SU(3)$_C$ representation r of ϕ. Generically it is desirable to include couplings between the mediators and the SM quarks so that they can decay. Such couplings depend on r, and are thus more model-dependent. We will assume that they are small enough so as to play little role in dark matter production at colliders.

When m_ϕ is large compared to the energies of interest, ϕ can be integrated out, leaving behind the non-renormalizable contact interaction C5:

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

where $G^a_{\mu\nu}$ is the gluon field strength and T_r is the Casimir corresponding to the choice of the representation of ϕ under SU(3). In [11], the bound on this operator from the CMS mono-jet analysis with $\not{E}_T > 500$ GeV [20] was derived to be,

$$\frac{\lambda_d T_r}{48\pi} \frac{1}{m_\phi^2} \le \frac{1}{(207\ \text{GeV})^2}. \tag{3}$$

Due to the large cut on $\not{E}_T$, the EFT description is only expected to be a good approximation when $m_\phi \gtrsim$ TeV. Thus, the bound really only applies self-consistently for very large λ_d and/or T_r. A meaningful estimation of the bound really requires the full calculation in the simplified model framework.

3. One-loop mono-jet rates

The mono-jet process, $pp \to j\chi\chi^*$, receives contributions at the parton level from processes:

$$\begin{aligned} gg &\to \chi\chi^* g, \\ gq(\bar{q}) &\to \chi\chi^* q(\bar{q}), \\ q\bar{q} &\to \chi\chi^* g, \end{aligned} \tag{4}$$

where q denotes any light quark, $q = u, d, s, c$. The one-loop ϕ-mediated diagrams contributing to gg channel are box, triangle and bubble type, while those contributing to $q\bar{q}$ and gq subprocesses are triangle and bubble type. Representative one-loop Feynman diagrams for all three initial states are shown in Fig. 1. Due to the charge conjugation symmetry, the triangle diagram with $gg\phi^\dagger\phi$ coupling does not contribute in gg subprocess, and so is not displayed in the Fig. 1.