On the Validity of Effective Operators for WIMP searches in t-channel models

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It is now clear that there are sever limitations to the validity of the effective operator description for dark matter interactions at the LHC. We extend recent analyses by investigating the case in which Dirac dark matter couples to standard model quarks via t-channel exchange of a scalar mediator. We measure the validity of the effective operator description of this model, at both $\sqrt{s} = 8$ TeV and 14 TeV. We also point out the general trend that in the regions where the effective operator description is valid, the dark matter relic abundance is typically large.

1 Introduction

The LHC is searching for direct DM production at unprecedented energies, yet it has proven difficult to constrain the WIMP sector in a model-independent way. One potential solution is the use of Effective Field Theories (EFTs), where a DM-SM interaction is written as a single effective operator, integrating out the mediator. This has the advantage of reducing the parameter space to a single mass ($m_{\rm DM}$) and an energy scale (Λ), and reducing the number of WIMP models down to a small basis set. EFTs are inherently an approximation to a full UV-complete theory, and hence must be used with caution. Given that the LHC is operating at very large energies, it is important to ensure that constraints on EFTs are internally consistent and fall in a region where the EFT approximation is valid.

This issue has been investigated in Refs. [1, 2] where the validity of the EFT has been tested in the s-channel. It was found that only a small fraction of events were at energies where the EFT approximation is valid. In addition, Refs. [3, 4] have compared constraints on some EFTs to those on simplified models, and found that constraints on Λ using UV complete models can either be substantially stronger or substantially weaker than those on EFTs, depending on the choice of parameters.

In this article we extend the analysis of Refs. [1, 2] to the t-channel. We consider a model where Dirac DM couples to SM quarks via t-channel exchange of a scalar mediator. Our goal is to determine in what regions of parameter space the EFT approach is a valid description of this model. The EFT approximation is made by integrating out the mediator, and combining the mediator mass M with the coupling strength g into a single energy scale, $\Lambda \equiv M/g$. This is done by expanding the propagator term for the mediator in powers of $Q^2_{\rm tr}/M^2$ and truncating at the lowest order, where $Q_{\rm tr}$ is the momentum carried by the mediator:

$$\frac{g^2}{Q_{\rm tr}^2 - M^2} = -\frac{g^2}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M^4}\right)\right) \simeq -\frac{1}{\Lambda^2}. \quad (1)$$

Clearly, this approximation is only valid when $Q_{\rm tr}^2 \ll M^2$; yet this condition is impossible to test precisely in the true EFT limit, since M has been combined with g to form Λ. Instead, an assumption about g must be made. There is no lower limit to the coupling strength, so regardless of the scale of Λ, it is always possible that M is small enough that the EFT approximation does not apply.

Alternatively, the most optimistic choice is to assume that $g \simeq 4\pi$, the maximum possible coupling strength such that the model still lies in the perturbative regime. As a middle ground, we test whether the EFT approximation is valid for values of $g \gtrsim 1$, a natural scale for the coupling in the absence of any other information. In this case, the condition for the validity of the EFT approximation becomes $Q_{\rm tr}^2 \lesssim \Lambda^2$, which we will adopt in the following to assess the validity of the use of EFT at LHC for DM searches.

2 Validity of the EFT: analytical approach

2.1 Operators and cross sections

In this article we will consider the following effective operator describing the interactions between Dirac dark matter χ and left-handed quarks q

$$\mathcal{O} = \frac{1}{\Lambda^2}\left(\bar{\chi}P_L q\right)\left(\bar{q}P_R\chi\right). \quad (2)$$

Only the coupling between dark matter and the first generation of quarks is considered.

The operator in Eq. (2) can be viewed as the low-energy limit of a simplified model describing a quark doublet Q_L coupling to DM, via t-channel exchange of a scalar mediator S_Q,

$$\mathcal{L}_{\rm int} = g\,\bar{\chi}Q_L S_Q^* + h.c. \quad (3)$$

and integrating out the mediator itself. We consider only coupling to the first generation of quarks, $Q_L = (u_L, d_L)$. This model is popular as an example of a simple DM model with t-channel couplings, which exist also in well-motivated models such as supersymmetry where the mediator particle is identified as a squark, and the DM is a Majorana particle.

The standard search channel for such a scenario is missing energy plus a single jet, although there are other promising complementary search channels. The dominant process contributing to the missing energy plus monojet signal is $q\bar{q} \to \chi\bar{\chi}g$. We have calculated the differential cross section for these processes.

2.2 Results and discussion

To test whether the EFT approximation is valid in monojet searches, we define the ratio of the cross section truncated so that all events pass the condition, to the total cross section:

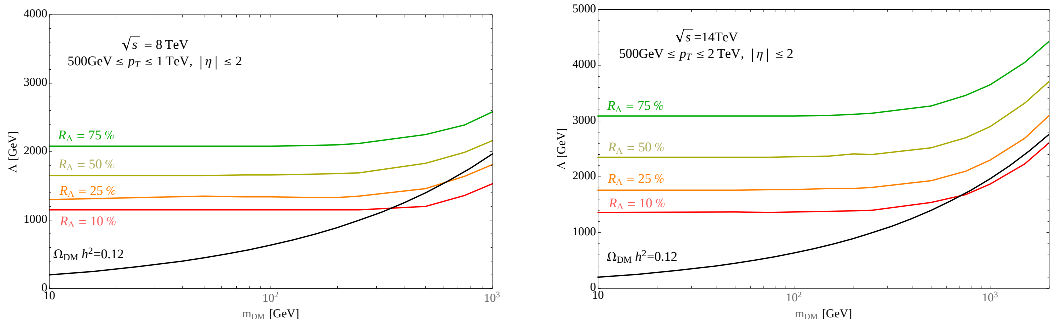

Figure 1: Contours for R_Λ. The black solid curves indicates the correct relic abundance.

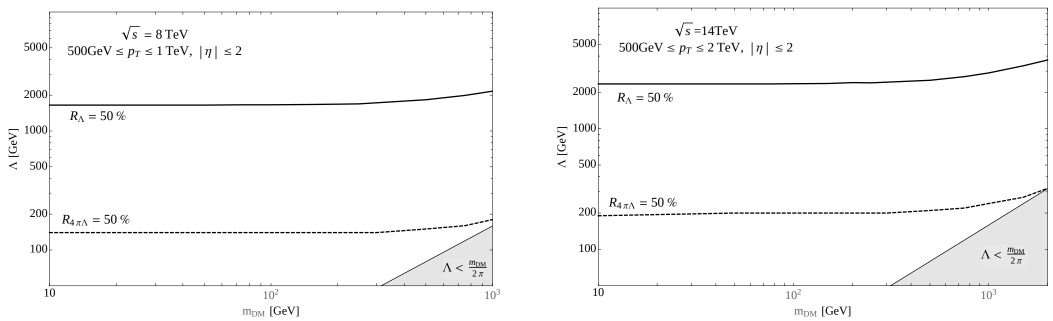

Figure 2: Contours for R_Λ, varying the cutoff $Q_{\rm tr} < \Lambda$ and $Q_{\rm tr} < 4\pi\Lambda$. The grey shaded area shows $\Lambda < m_{\rm DM}/(2\pi)$, often used as a benchmark for the validity of the EFT.

$$R_\Lambda \equiv \frac{\sigma|_{Q_{\rm tr}<\Lambda}}{\sigma} = \frac{\int_{p_{\rm T}^{\rm min}}^{p_{\rm T}^{\rm max}} {\rm d}p_{\rm T} \int_{-2}^{2} {\rm d}\eta \left.\frac{{\rm d}^2\sigma}{{\rm d}p_{\rm T}{\rm d}\eta}\right|_{Q_{\rm tr}<\Lambda}}{\int_{p_{\rm T}^{\rm min}}^{p_{\rm T}^{\rm max}} {\rm d}p_{\rm T} \int_{-2}^{2} {\rm d}\eta \frac{{\rm d}^2\sigma}{{\rm d}p_{\rm T}{\rm d}\eta}}. \tag{4}$$

The integration limits on these quantities are chosen to be comparable to those used in standard searches for WIMP DM by the LHC collaborations (see, for instance, Ref. [5]).

In Fig. 1 we plot isocontours of four fixed values of R_Λ as a function of both $m_{\rm DM}$ and Λ. Contrasted with the s-channel case [1, 2], the ratio has less DM mass dependence, being even smaller than in the s-channel case at low DM masses and larger at large DM masses, without becoming large enough to save EFTs.

In Fig. 1 we also show the curves corresponding to the correct DM relic density. For given $m_{\rm DM}$, larger Λ leads to a smaller self-annihilation cross section and therefore to larger relic abundance. It is evident that the large-Λ region where the EFT is valid typically leads to an unacceptably large DM density.

In the most optimistic scenario for EFTs, the coupling strength g takes the maximum value (4π) such that the model remains in the perturbative regime. To demonstrate how our results depend on the coupling strength, in Fig. 2 we plot isocontours for $R = 50\%$, for two cases:

1) the standard requirement that $Q_{\rm tr}^2 < \Lambda^2$, equivalent to requiring $g \simeq 1$, and **2)** requiring $Q_{\rm tr}^2 < (4\pi\Lambda)^2$, equivalent to requiring $g \simeq 4\pi$.

The grey shaded area indicates the region where $\Lambda < m_{\rm DM}/(2\pi)$. This is often used as a benchmark for the validity of the EFT approximation, since in the s-channel, $Q_{\rm tr}$ is kinematically forced to be greater than $2m_{\rm DM}$.

3 Conclusions

In this article we have extended the investigation of the validity of the EFT approach for DM searches at the LHC. We have considered here the case of Dirac DM couplings to the standard model via the t-channel.

We have computed the relic density over the parameter space of the model, assuming that the only interactions between DM and the SM are those mediated by the t-channel operator (2), and found that the region of EFT validity corresponds to an overly large relic density. This conclusion is rather general and may be evaded by assuming additional DM annihilation channels.

Similar to what happens in the s-channel case, our findings indicate that in the t-channel the range of validity of the EFT is significantly limited in the parameter space $(\Lambda, m_{\rm DM})$, reinforcing the need to go beyond the EFT at the LHC when looking for DM signals. This is especially true for light mediators as they can be singly produced in association with a DM particle, leading to a qualitatively new contribution to the mono-jet processes. Mediators can even be pair-produced at the LHC through both QCD processes and DM exchange processes. All of this rich dynamics leads to stronger signals (and therefore, in the absence thereof, to tighter bounds) than the EFT approach.

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