Dark Matter at the LHC and IceCube – a Simplified Models Interpretation

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We present an interpretation of searches for Dark Matter in a simplified model approach. Considering Majorana fermion Dark Matter and a neutral vector mediator with axial-vector interactions we explore mono-jet searches at the LHC and searches for neutrinos from Dark Matter annihilation in the Sun at IceCube and place new limits on model parameter space. Further, we compare the simplified model with its effective field theory approximation and discuss the validity of the latter one.

1 Introduction

Weakly interacting massive particles (WIMPs) are popular candidates to account for Dark Matter (DM) in the universe. In the absence of a complete theory of new physics – like supersymmetry – there are basically two ways of describing the phenomenology of a WIMP DM scenario. One is the use of effective operators describing the interactions between the standard model (SM) and the WIMP in the framework of effective field theory (EFT). Another approach is to use simplified models. Here a limited set of new particles is introduced that allows to describe the phenomenology via renormalizable interactions. A simplified model can either be seen as self-consistent extension to the SM or a parametrization of a particular corner in the parameter space of a more complete theory.

Although the EFT framework has been successfully used for the description of DM interactions at rather low scales, it has been pointed out that the use of EFT for the derivation of LHC limits could be problematic [1–3]. In this article we consider a model that extends the SM by a Majorana fermion DM and a vector mediator which couples to the DM and the SM quarks with axial-vector interactions, with couplings g_χ and g_q, respectively. For such a model, LHC searches are expected to be more sensitive than direct detection experiments as the model does not provide any contribution to spin-independent WIMP-nucleon scattering.

In this article we present LHC limits on the parameters space of this model and compare them to the respective limits obtained in the EFT approximation. For realistic values of the couplings, $g_\chi, g_q \lesssim 1$, the LHC provides limits on the messenger mass in the ballpark of 100 GeV to 1 TeV. As these are accessible energies at LHC collisions, contributions from on-shell messenger production can be large. Hence, limits from the simplified model and the EFT can differ significantly as we will discuss in section 2.

As a complementary constraint on the parameter space we consider limits on the spin-dependent WIMP-nucleon scattering from Dark Matter annihilation in the Sun provided by the IceCube collaboration [4]. These limits are particularly constraining for large DM masses where the LHC looses its sensitivity. We discuss them in section 3.

2 LHC mono-jet constraints

In this work we interpret two searches for mono-jet plus missing transverse momentum signatures performed by ATLAS [5] and CMS [6] at the 8 TeV LHC. To this end we performed a Monte Carlo simulation of the signal and imposed the search cuts detailed in [5, 6]. Based on the background analysis provided in these references we are thus able to set 95% C.L. exclusion limits on the parameters of the model. For details we refer to [7].

The considered model has four independent parameters. The DM mass, m_χ, the mediator mass, M_V, and the couplings of the mediator to the DM, g_χ, and the SM quarks g_q. We assume universal couplings to all SM quarks and neglect couplings to leptons. We show our results for various slices of the parameter space where we fix the product of the couplings, $g_\chi g_q$ and the mediator width, Γ_V. We choose this parametrization as the cross section for DM production directly depends on these parameters. However, not all values of Γ_V and g_χ, g_q are actually consistent within this model as we will show below. In the EFT approximation we integrate out the messenger and obtain a 4-fermion contact interaction with an effective coupling $d = g_\chi g_q/M_V^2$. Hence, the parameter space reduces to two parameters, m_χ and d.

In Figure 1 we show the exclusion limits for the EFT (dashed lines) and the simplified model (solid lines) for four slices of the considered parameter space. Whilst the EFT limit extents to very high DM masses, above a TeV the limit from simplified models goes down very drastically for $M_V \lesssim 2m_\chi$. In this region the EFT approximation is not valid. However, also for $M_V \gg m_\chi$ we find significant deviations in the resulting limit on M_V. This is due to the fact that the limit on M_V placed for $\sqrt{g_\chi g_q} \leq 1$ lies in the region of reachable LHC energies. Hence, the contribution from on-shell mediator production enhances the cross section. This is the dominant effect for the parameter slices with $\Gamma_V = 0.01 M_V$ (left panels of Fig. 1). The effect becomes more pronounced for the smaller coupling, $\sqrt{g_\chi g_q} = 0.2$, (see lower panels) as the limits are placed at lower M_V where the contribution from on-shell mediator production is larger.

For the slices with the larger width $\Gamma_V = 0.5 M_V$ (see right panels of Fig. 1) the limits from simplified models and the EFT are more similar for $M_V \gg m_\chi$. Note that for very small M_V the EFT overestimates the limit. This can be seen in the case $\sqrt{g_\chi g_q} = 0.2$, $\Gamma_V = 0.5 M_V$ (lower right panel) where the CMS limit for the simplified model completely vanishes whilst the EFT would exclude $M_V \gtrsim 200$ GeV.

As mentioned above not all combinations of m_χ, M_V, $\sqrt{g_\chi g_q}$ and Γ_V are consistent within the model. In Figure 1 we marked in blue the regions where no such solution exist. Note that the region $M_V > 2m_\chi$ —the region where the EFT shows its best agreement— is strongly constrained and almost excluded for a reasonably small width of $\Gamma_V = 0.01 M_V$.

3 Constraints from DM annihilation in the Sun

If WIMPs scatter in heavy objects such as the Sun, they can loose enough energy to become gravitationally trapped and accumulate inside the Sun. This leads to a locally enhanced WIMP density providing significant DM annihilation. Neutrinos that are produced as primary or secondary products of such annihilations can escape the Sun and be detected on Earth. On

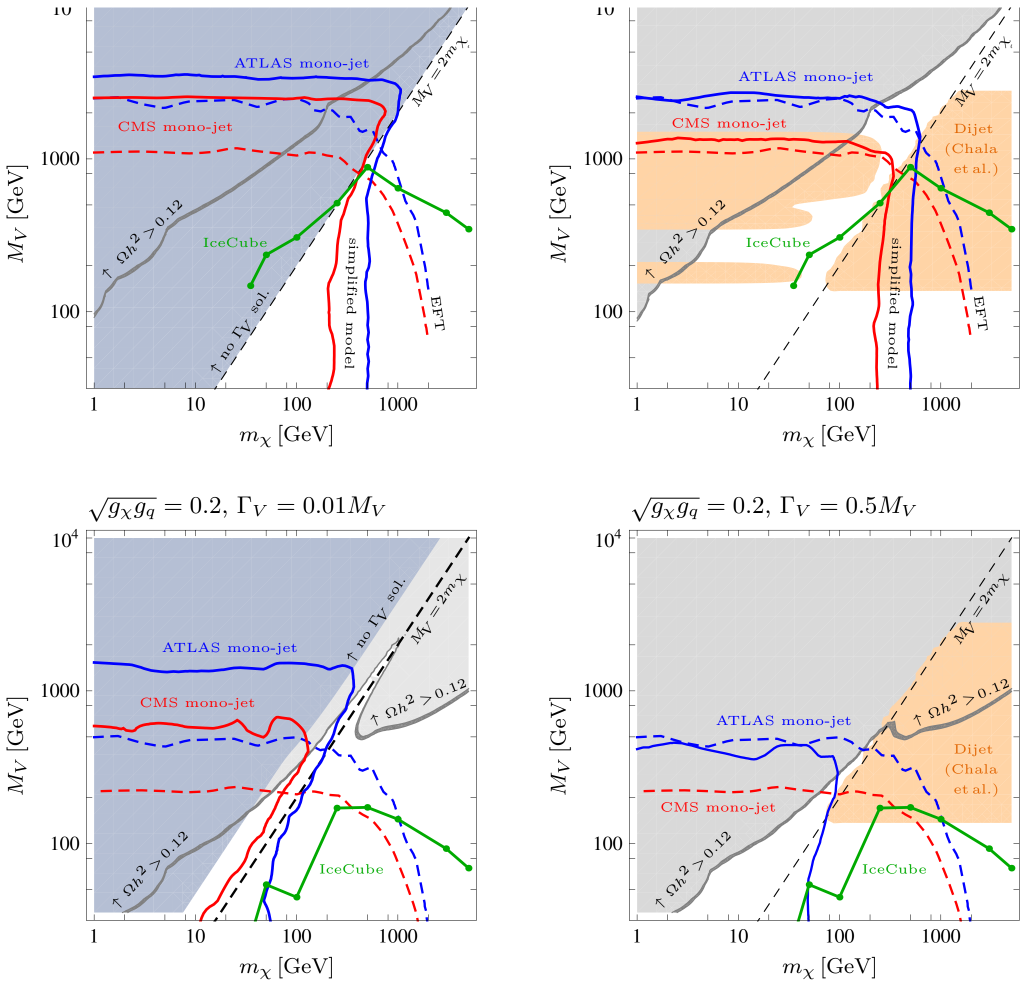

Figure 1: Exclusion limits in the m_χ-M_V plane in four slices of the considered parameter space regarding $\sqrt{g_\chi g_q}$ and Γ_V. The 95% CL exclusion limits from mono-jet searches at ATLAS (blue lines) and CMS (red lines) are shown for the simplified model (solid lines) and the EFT approximation (dashed lines). Further, we show 90% CL exclusion limits from the IceCube Neutrino Observatory (green lines). The dark grey shaded band denotes the region where the relic density matches the dark matter density within $\pm 10\%$. In the light-grey shaded region above it, the Dark Matter is over-produced. The blue shaded region in the left panels do not allow for a consistent solution for the mediator width as a function of $M_V, m_\chi, \sqrt{g_\chi g_q}$ within the model. The orange shaded regions are exculded from searches for resonances in di-jet signatures taken from Ref. [8].

large time-scales, an equilibrium between the capturing and annihilation can be reached. In this case, a limit on the neutrino flux can be translated into a limit on the scattering cross section of WIMPs inside the Sun. As the Sun contains large amounts of hydrogen, it provides sensitivity to spin-dependent WIMP-proton scattering.

We use data from the IceCube Neutrino Observatory, which are interpreted in two benchmark scenarios according to dark matter annihilation into $b\bar{b}$ or WW only. In most of the parameter space of our model, annihilations into $b\bar{b}$ or $t\bar{t}$ dominate. Therefore we reinterpret the limits from Ref. [4] in order to estimate a limit for annihilation into $t\bar{t}$ by applying conversion factors for $t\bar{t}$ [9] to the WW-channel. We then conservatively apply the limit from the dominant contribution to annihilation (among $b\bar{b}$ and $t\bar{t}$) for each point in parameter space. The resulting limits are shown in Fig. 1 (green lines). In the region of large m_χ where LHC searches loose sensitivity, the limits from IceCube are able to exclude mediator masses up to $M_V \simeq 200\,\text{GeV}$ ($1\,\text{TeV}$) for $\sqrt{g_\chi g_q} = 0.2$ (1).

4 Conclusion

We have considered a model with a vanishing spin-independent WIMP-nucleon cross section and set new limits on the model parameter space from LHC mono-jet searches as well as IceCube. From the LHC, for $\sqrt{g_\chi g_q} = 1$ we can exclude mediator masses up to around 3 TeV for $m_\chi \lesssim 1\,\text{TeV}$ while for $\sqrt{g_\chi g_q} = 0.2$ we exclude M_V in the range of 500 GeV to 1.5 TeV with a strong dependence on the mediator width. We compared these limits to the ones obtained in the EFT and found that these are neither entirely conservative nor optimistic in the whole considered parameter space. Limits from IceCube are complementary probing particularly large m_χ where the LHC is not sensitive at all reaching up to $M_V \simeq 1\,\text{TeV}$ for $\sqrt{g_\chi g_q} = 1$.

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