Closing in on \(t\)-channel simplified dark matter models

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**ABSTRACT**

A comprehensive analysis of cosmological and collider constraints is presented for three simplified models characterised by a dark matter candidate (real scalar, Majorana fermion and real vector) and a coloured mediator (fermion, scalar and fermion respectively) interacting with the right-handed up quark of the Standard Model. Constraints from dark matter direct and indirect detection and relic density are combined with bounds originating from the re-interpretation of a full LHC run 2 ATLAS search targeting final states with multiple jets and missing transverse energy. Projections for the high-luminosity phase of the LHC are also provided to assess future exclusion and discovery reaches, which show that analogous future search strategies will not allow for a significant improvement compared with the present status. From the cosmological point of view, we demonstrate that thermal dark matter is largely probed (and disfavoured) by constraints from current direct and indirect detection experiments. These bounds and their future projections have moreover the potential of probing the whole parameter space when combined with the expectation of the high-luminosity phase of the LHC.

1. Introduction

The nature of dark matter and the way it is connected to the Standard Model (SM) is one of the most puzzling issues in particle physics today. Dark matter searches consequently hold a central place in the present astroparticle and particle physics program. However, despite of convincing indirect evidence for its existence [1], dark matter still evades any direct detection probes. Experimental searches at colliders, in underground nuclear recoil experiments and with gamma-ray telescopes therefore put stronger and stronger constraints on the viability of any dark matter model. Those bounds are very often explored, in a model-independent approach, as limits on a set of simplified models for dark matter phenomenology. In those simplified models, the dark matter is considered as a massive particle whose interactions with the SM arise through a mediator particle. In so-called \(s\)-channel setups [2, 3, 4], the mediator is a colour singlet and couples to a pair of either dark matter or SM particles. On the contrary, in a \(t\)-channel configuration, the mediator interacts instead with one SM state and the dark matter [5].

In this work, we consider three simplified \(t\)-channel scenarios, that we coin \(F_{3S_uR}^{35}, S_{M_uR}^{35}\) and \(F_{3Y_uR}^{35}\), and that are defined in ref. [5]. Their common features are the following. First, the dark matter candidate is a real particle, singlet under the SM gauge group, so that its stability can be ensured through a \(Z^2\) symmetry. This contrasts with other \(t\)-channel models including a complex dark matter field and thus exhibiting instead a continuous unbroken global \(U(1)\) symmetry. Second, the mediator couples the dark matter candidate to the right-handed up-quark field, so that the mediator is itself an \(SU(2)_L\) weak singlet. The defining features of the three scenarios then consist in the spins of the dark matter and of the mediator, which affect the kinematics of any signal and therefore current bounds and projections for future searches. We comprehensively derive updated constraints on the three model parameter spaces, considering both cosmological and collider observations. Moreover, we additionally provide projections for the future high-luminosity phase of the LHC (HL-LHC).

The rest of the paper is organised as follows. In the next section we briefly define the \(DMSimpt\) general framework for \(t\)-channel dark matter models, while in section 3 we describe our analysis of the collider constraints and provide results with current exclusion bounds. In section 4 we study the astrophysical and cosmological constraints on these simplified models under the assumption of thermal relic dark matter. In section 5 we combine these results and include future experiment expectations, illustrating the impact of the collider/cosmology combination on representative projections of the model parameter space. We summarise our main findings and discuss future developments in section 6.

2. The \(t\)-channel simplified models

The three simplified models under study are defined within the \(DMSimpt\) framework [5], which provides a generic \(t\)-channel dark matter simplified model. In the latter, the SM is extended by six real or complex dark matter fields, collectively denoted by \(X\) and all singlets under the SM gauge group \(SU(3)_c \times SU(2)_L \times U(1)_Y\), plus the corresponding mediator particles, collectively denoted by \(Y\), all lying in the fundamental representation of \(SU(3)_c\) and coupling the \(X\) particles to the SM quarks.

The scenarios considered in the present analysis are re-
the dark matter particle $X$ is real and solely couples to the right-handed up-quark. There is hence a unique mediator particle $Y$, singlet under $SU(2)_L$. The corresponding interaction Lagrangians for the $F_{3S,uR}$ (real scalar dark matter $S$ with a fermionic mediator $\psi$), $S_{3M,uR}$ (Majorana dark matter $\tilde{S}$ with a scalar mediator $\phi$) and $F_{3V,uR}$ (real vector dark matter $\tilde{V}_\mu$ with a fermionic mediator $\psi$) models respectively read

\[
\mathcal{L}_{F_{3S,uR}} = \left[ \hat{\lambda}_\psi \tilde{u}_R \psi S + \text{h.c.} \right], \\
\mathcal{L}_{S_{3M,uR}} = \left[ \hat{\lambda}_\phi \tilde{u}_R \phi \tilde{S} + \text{h.c.} \right], \\
\mathcal{L}_{F_{3V,uR}} = \left[ \hat{\lambda}_\psi \tilde{u}_R \psi \tilde{V}_\mu + \text{h.c.} \right].
\]

In those expressions, $\hat{\lambda}_\psi$, $\hat{\lambda}_\phi$ and $\hat{\lambda}_\bar{\psi}$ stand for real coupling strengths, that together with the dark matter ($M_S, M_{\tilde{S}}$ and $M_{\tilde{Y}}$) and mediator ($M_{\psi}, M_{\phi}$ and $M_{\bar{\psi}}$) masses lead to three free parameters for each of the considered models. We collectively denote this set of free parameters by $(m_X, m_Y, \lambda)$.

In this work, we allow the two masses $m_X$ and $m_Y$ to vary in the $[1, 10^4]$ GeV range and consider $\lambda$ coupling values in the $[10^{-4}, 4\pi]$ range. We use the corresponding next-to-leading-order (NLO) UFO [6] model files with five massless quarks for collider studies with MG5_AMC [7], and both the leading-order (LO) UFO and CALCHEP [8] model files with six massive quarks for simulations with MadDM [9] and MicrOMEGAs [10] respectively. All those model files have been obtained with FeynRules [11] and are available from https://feynrules.irmp.ucl.ac.be/wiki/DMsimp.

3. Collider bounds

Three types of processes are considered for the determination of the collider constraints on the models. They consist in the production of a pair of dark matter particles ($pp \rightarrow X \bar{X}$), of a pair of mediators ($pp \rightarrow YY$) and the associate production of a dark matter and a mediator ($pp \rightarrow X \bar{Y}$). Mediator pair-production is itself composed of three components, namely a QCD contribution, a dark-matter-induced contribution (with the propagation of the dark matter particle in the t-channel) and their interference. When the mediator is produced, it subsequently decays into a dark matter candidate and a right-handed up-quark ($Y \rightarrow Xu_R$), the decay process being always factorised from the production one. This however assumes that the decay width of the mediator $\Gamma_Y$ is small relatively to its mass, such that the narrow-width approximation (NWA) holds.

All simulations are performed with MG5_AMC and follow the procedure described in ref. [5], the NLO matrix elements being convoluted with the NNPDF 3.0 set of parton densities [13] through the LHAPDF 6 library [14]. Moreover, to ensure the validity of the NWA and the factorisation of the production and decay processes, all simulations have been performed at a fixed $\Gamma_Y/m_\gamma$ ratio of 1%, assuming that the final-state kinematics is not impacted by slightly larger values of this ratio. In the following, we reweight those generated events so that the cross section evaluation makes use of a $\lambda$ value yielding $\Gamma_Y/m_\gamma = 5\%$. This choice requires a more important coupling and leads to weaker cosmological constraints, which thus allows for a larger cosmologically-viable region of the parameter space to be probed by LHC searches (see section 4 and section 5).

We obtain constraints on the models through the recast of an ATLAS search targeting final states with multiple jets and missing transverse energy [15] by means of the MADANALYSIS 5 framework [16]. The significance of the signal is derived for each of the ten signal regions (SRs) of the search through the CLs method [17], and we include in our predictions signal systematics stemming from scale variations and the parton density fits [18]. The yields of the backgrounds for each SR, with their uncertainties, and the number of observed events, are provided by the ATLAS search.

Due to the different dependence of the cross sections on the $\lambda$ coupling and on the masses of the new particles, the relative weights of the $XX$, $XY$ and $YY$ contributions in the determination of the constraints change along the parameter space, as shown in the top row of fig. 1. The combination of the various contributions to the $YY$ process constrains the majority of the parameter space for all the considered scenarios. In contrast, the $XX$ process only becomes competitive in the compressed region and for large mediator masses, while the $XY$ one provides instead stronger constraints for scenarios featuring a large mass gap and a large mediator mass. The region with small dark matter and mediator masses is likely to be excluded too, but the number of initial MC events required to test the region with enough statistics is too demanding in terms of computing resources.

The combination of the bounds for any given scenario is obtained in two steps. We first sum the number of events populating each signal region as obtained from the individual $XX$, $XY$ and $YY$ contributions, and then compute the corresponding significance. We display the results in the bottom row of fig. 1, in which we additionally highlight the best signal region driving the bound. The dominance of the $YY$ component in the determination of the bounds is reflected in the similarities of the results for the $F_{3S,uR}$ and $F_{3V,uR}$ models that share the same mediator particle. For the $S_{3M,uR}$ class of scenarios, the bounds are sizeably weaker, given the smaller cross section for the pair production of a scalar mediator that features a smaller number of degrees of freedom than a fermion.

The combined signal kinematics for any given scenario depends on the subprocess that dominates, which is reflected in the variations in the best SRs driving the bounds along the parameter space. Regions requiring two very hard jets are more suitable when the $YY$ channel dominates and each mediator decay leads to a significantly hard jet. In contrast, SRs dedicated to final states featuring four jets give a better outcome in the compressed regime. While these regions
4. Cosmological bounds

For all three models, we sample the three-dimensional parameter space with MICROMEGAS and require that the dark matter candidate makes up 100% of the measured dark matter abundance, $\Omega h^2_{\text{planck}} = 0.12$ [19]. The thermally averaged dark matter annihilation cross section $\langle \sigma v \rangle$ ($v$ being the relative velocity between two dark matter particles) is $d$-wave-suppressed for the real scalar case [25, 26, 27] and $p$-wave-suppressed for Majorana dark matter [26]. NLO corrections in the relic density computation might therefore be relevant [27, 28]. To account for these corrections, we include the loop-induced $XX \rightarrow gg$ and $XX \rightarrow \gamma Z$ processes, and the three-body $XX \rightarrow u_R \bar{u}_R \gamma$ and $XX \rightarrow u_R \bar{u}_R \gamma$ annihilations that could be potentially enhanced by virtual internal bremsstrahlung (VIB). For our predictions, we use the analytic expressions provided in refs. [25, 26, 29] that we have validated with MADDM.

Through our scans of the model parameter spaces, we single out regions where the elastic dark matter scattering cross section on protons is compatible with both the spin-independent (SI) and spin-dependent (SD) exclusion limits at 90% confidence level (CL) from the XENON1T [20] and PICO [23] experiments, our predictions relying on NLO cross sections [30] to properly model the impact of QCD radiation. In principle, coupling running effect should also be included [31]. The latter would lead to tighter exclusion limits, slightly augmenting their sensitivity for large dark matter masses. We have however omitted them from our computations, although we have verified that they do not impact our conclusions. Finally, we impose in our scanning procedure that predicted indirect detection signals are compatible with the current (model-dependent) exclusion limits at 95% CL.

In the case of the $F3S_{uR}$ and $S3M_{uR}$ models, spectral features in the gamma ray spectrum bring one of the strongest bounds as tree-level $XX \rightarrow u_R \bar{u}_R \gamma$ annihilations are velocity suppressed. We therefore derive constraints by considering a combination of direct annihilations into photons and

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**Figure 1:** Top row: Individual 95% CL bounds arising from the three different channels $XX$ (red), $XY$ (green) and $YY$ (blue) for the $F3S_{uR}$ (left), $S3M_{uR}$ (centre) and $F3V_{uR}$ (right) scenarios, presented in the $(m_{\psi}, m_{\chi})$ plane for a fixed mediator width-to-mass ratio. Bottom row: Combined 95% CL bounds, with the signal region exhibiting the best sensitivity depicted by the background colour. In all panels, the black dashed lines correspond to the value of the couplings which is required to obtain a width over mass ratio of 5%, the 4$\pi$ value being highlighted to roughly identify the perturbative regime. The coloured dashed lines identify the area for which the number of simulated Monte Carlo events populating the best region is larger than 100 (allowing for a Poisson uncertainty smaller than 10%).
into a $u_R \bar{u}_R$ system, the latter being potentially enhanced by VIB contributions. The total annihilation cross section $\langle \sigma v \rangle_{tot} = \langle \sigma v \rangle_{u_R \bar{u}_R} + 2 \langle \sigma v \rangle_{\gamma \gamma}$ is then confronted with the most recent Fermi-LAT [21] and HESS [22] data from the Galactic Centre. We assume that the gamma-ray spectrum related to the $u_R \bar{u}_R$ contribution presents a sharp feature close to the dark matter mass, even though the exact position of this feature depends on $r \equiv m_Y / m_X [33]$. The obtained constraints are in the worst case conservative, although for most scanned over scenarios they consist in a good approximation. The three-body signal indeed dominates over the di-photon one, at least at small $r$ values, so that the peak is often very close to the dark matter mass. The derivation of more precise constraints would require a recast of the experimental results, which lies beyond the scope of this study.

Other relevant bounds can be obtained by investigating dark matter annihilations into gluons, as this could be constrained by the Fermi-LAT analysis of dwarf spheroidal galaxies (dSphs) data [24]. Similarly to the gamma-ray case, we evaluate $\langle \sigma v \rangle_{tot} = \langle \sigma v \rangle_{u_R \bar{u}_R} + \langle \sigma v \rangle_{gg}$ and compare our predictions with Fermi-LAT dSph results for the $gg$ annihilation channel [9]. These constraints being comparable with those arising from gamma-ray line searches, they are omitted from the discussion. Finally for the $F_3V_{uR}$ model, $XX \rightarrow u_R \bar{u}_R$ annihilations occur in an $s$-wave configuration. The most stringent indirect detection bounds are thus given by Fermi-LAT dSph searches, this time in the $u_R \bar{u}_R$ final state.

Our results are shown in fig. 2. The coloured region represents scenarios that can account for the correct relic density when assuming a standard freeze-out mechanism. For the $F_3S_{uR}$ model, NLO corrections drastically modify the contours of the viable parameter space region at large $r$, selecting $\lambda$ values smaller than for the LO case. This stems from the $XX \rightarrow gg$ contributions, that are driven by the strong coupling constant $\alpha_s$ and that enhance the annihilation cross section. On the contrary, NLO corrections for the Majorana dark matter case do not impact the results much. In the large $r$ regime, we obtain deviations in the $\lambda$ value of at most 15% with respect to the LO case, whilst scenarios featuring a small $r$ value are unaffected, the annihilation cross section being dominated by $\alpha_s$-dependent co-annihilations. Following the same reasoning, it turns out that the actual value of $\lambda$ is irrelevant when co-annihilations of the mediator via QCD processes drive the relic density.

The $F_3V_{uR}$ model is the one that features the largest parameter space for which the relic density as measured by the Planck collaboration can be accommodated. For any given $(m_X, m_Y)$ mass configuration, the $\lambda$ value that is needed to

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\[ E \] is the energy fraction.

\[ \langle \sigma v \rangle_{tot} = \langle \sigma v \rangle_{u_R \bar{u}_R} + 2 \langle \sigma v \rangle_{\gamma \gamma} \]

\[ \langle \sigma v \rangle_{u_R \bar{u}_R} = \frac{1}{2} \langle \sigma v \rangle_{gg} \]

\[ \langle \sigma v \rangle_{gg} = \frac{4 \pi \alpha_s^2}{9 \pi^2} \]

\[ \alpha_s = \frac{\pi}{N_c} \]

\[ \lambda = \frac{m_Y}{m_X} \]

\[ E_{\text{Planck}} = \frac{E}{m_X} \]

\[ E_{\text{Planck}} = \frac{E}{m_Y} \]
obtain $\Omega h^2_{\text{Planck}}$ is smaller than in the scalar and Majorana dark matter cases. The annihilation strength of vector dark matter is indeed larger, except in the co-annihilation regime where the model is indistinguishable from the $F_{3S, uR}$ setup that also features a fermionic mediator.

Our findings show a nice complementarity between direct and indirect dark matter searches in the case of the $F_{3S, uR}$ and $F_{3V, uR}$ models. Gamma-ray searches (yellow shaded region) are able to probe and disfavour at 95% CL dark matter candidates with masses ranging down to 1 GeV, except for compressed spectra with $r - 1 \lesssim 0.3$ and very small couplings below about $10^{-2}$ (bottom row of fig. 2). This unexplored region consists in one of the two co-annihilation-dominated regions which are still open and might give rise to interesting LHC signatures through long lived particles (LLPs) [34]. For the $S_{3M, uR}$ model, indirect detection plays a minor role, excluding a limited part of the parameter space where dark matter is light. The two separated excluded regions correspond to Fermi-LAT limits arising from $XX \rightarrow \gamma\gamma$ (large $r$ values) and $XX \rightarrow u_R\bar{u}_R^Y$ (small $r$ values) annihilations respectively. Finally, $F_{3S, uR}$ scenarios can be probed by the HESS experiment, as depicted by the disfavoured highland in the parameter space at $m_X > 300$ GeV.

Direct and indirect detection bounds both exclude the intermediate mass range, although direct detection bounds additionally contribute to cut down the parameter space for large dark matter masses, close to 1 TeV or even higher, where one finds a second viable co-annihilation regime. Remarkably, direct detection results from XENON1T (blue shaded region) and PICO (green shaded region) are also able to probe the co-annihilation regime. The whole freeze out parameter space is hence disfavoured at 90% CL for dark matter masses between 8 GeV and 1000 (500) GeV for the $F_{3S, uR}$ ($F_{3V, uR}$) model.

Spin-dependent direction detection exclusion bounds are the most stringent constraints on the $S_{3M, uR}$ model parameter space. Majorana dark matter is strongly disfavoured for masses between 8 and 300 GeV, even for the co-annihilation regime that could give rise to LLP collider signatures. The latter regime is even further constrained, for dark matter masses ranging up to 10 TeV, by the XENON1T SI bounds, these constraints being due to the scalar nature of the mediator.

5. Combining dark matter searches

We illustrate in fig. 3 the complementarity of the considered cosmological and collider constraints on the models, after mapping the cosmological bounds of section 4 onto an $(m_X, m_Y)$ plane for a fixed $\Gamma_Y/m_Y$ ratio of 5%\textsuperscript{4}. However, contrary to the previous section, we allow for under-abundant dark matter and therefore only consider the relic density constraint as an upper bound. We hence implicitly assume the existence of some other dark matter component, with different properties and interactions.

Under these assumptions, we obtain allowed parameter space regions for all scenarios. These regions feature mediator masses greater than 1.5 TeV (scalar mediator) and 2 TeV (fermion mediator), and a neither too compressed nor too split new physics spectrum. The mediator mass is mostly constrained by collider searches, while the dark matter mass is restricted by the combination of the relic density (lower bound) and the interplay between the SD and SI direct detection (upper bound) constraints. The only exception concerns the small mass gap regime in which the collider constraints tend to be competitive (despite of potentially non-perturbative couplings). For all scenarios, indirect detection constraints are too weak to play any role. Gamma-ray fluxes are indeed reduced by a $\left(\Omega h^2_{\text{model}}/\Omega h^2_{\text{Planck}}\right)^2$ factor for under-abundant dark matter, contrarily to the direct detection predictions that are only linearly rescaled\textsuperscript{5}.

This collider-cosmology complementarity of constraints is compatible with the nature of the considered experimental probes. Collider bounds are largely dominated by the impact of the $YY$ channel. On the contrary, direct detection experiments are more sensitive to scenarios featuring large couplings and/or a small $X/Y$ mass splitting, as the direct detection cross section scales as $\lambda^4$ and exhibits a polynomial in $\tau$ in its denominator. Moreover, when allowing for under-abundant dark matter, the relic density favours large couplings as well and opens the door to a much wider set of viable solutions.

In the same fig. 3, we provide projections for future experiments. We show projected 2$\sigma$ exclusion and 5$\sigma$ discovery reaches for the HL-LHC, which corresponds to a luminosity of 3 ab$^{-1}$. We extrapolate the current reach under two assumptions for the manner the systematic uncertainties on the background $\epsilon_{\text{bkg}}$ could evolve. In a first case, we consider that it is the same as in the initially considered 139 fb$^{-1}$ ATLAS search, while in the second case, we assume that it reaches a floor of 5$\%$ for each SR. The results show that considering the recast cut-and-count ATLAS analysis, the bounds will not improve significantly even with an optimistic assumption on the systematics. Equivalently, this shows that the discovery reach is very close to the current exclusion limits. Different, more complex, analysis strategies should therefore be considered to better assess the potential of future searches in probing a wider region of the parameter space. For example, the ATLAS search that we have used in our analysis also includes a supersymmetry-inspired signal region relying on a boosted decision tree, which we did not consider in our model-independent approach.

On the other hand, the projected cosmological bounds have a much larger potential. We present the expected sen-
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Figure 3: Top row: Bounds arising from cosmological observations, represented in the $(m_\psi, m_\phi)$ plane for a fixed mediator width over mass ratio of 5%, on the $F3S_{\text{UR}}$ (left), $S3M_{\text{UR}}$ (centre) and $F3V_{\text{UR}}$ (right) model parameter space. We allow for under-abundant dark matter, the band which reproduces the relic density as measured by the Planck collaboration lying between the (almost indistinguishable) thin and thick magenta lines. Future projections of the constraints are provided as dashed lines. Bottom row: Combination of cosmological and collider bounds and their projections. The collider projections correspond to exclusion and discovery reaches for a LHC luminosity of 3000 fb$^{-1}$ (\textit{i.e.} the HL-LHC phase) and assume a level of systematics on the background either equal to the considered ATLAS search at current luminosity or fixed to 5%.

sensitivity of future SI (LZ [36]) and SD (LZ, PICO-500 [37] and COSINUS [38]) direct detection experiments, the latter being extracted from ref. [39] for the $O_4$ operator (\textit{i.e.} for standard SD interactions). The interplay of the projected SD bounds and the relic density constraints can completely exclude the $S3M_{\text{UR}}$ scenario, while the improvement of the SI bounds would drastically limit the options allowed by the HL-LHC expectation for the $F3S_{\text{UR}}$ model. Similarly, high-energy gamma-ray experiments, such as CTA [40, 41] and SWGO [42], and the LSST+Fermi-LAT dSphs survey [43] will be able to explore the model parameter space well above the TeV regime, in a region that is out of reach of LHC searches. In particular, projections for indirect detection has the largest impact on the $F3V_{\text{UR}}$ scenario, being the dominant constraint for large mediator masses. It however still leaves a large window testable at the HL-LHC.

6. Conclusions

We have performed a comprehensive analysis of cosmological and collider bounds for three sets of $t$-channel simplified dark matter models in which the dark matter is a real field. We have investigated the complementarity between the different types of bounds and made projections for future collider and cosmological experiments. Our findings show that most parameter spaces are already strongly constrained by current bounds, and that future dark matter direct and indirect detection probe have a large potential to cover the still allowed regions of the parameter space. In this way, conclusive statements on the phenomenological viability of the considered class of $t$-channel models will be in order in the next decades.

One should however keep in mind that the models considered in this analysis are simplified and model-independent constructions. While being representative of different theoretically-motivated new physics scenarios, they necessarily lack non-minimal features, such as the presence of more mediators, a multi-component dark matter spectrum, or a wider range of interactions between the new particles and the SM. Such features can change the picture by introducing, for example, interference contributions which can weaken the constraints or effects due to large mediator widths which modify the final-state kinematics at colliders.

Finally, we did not investigate freeze-in dark matter scenarios, which we leave for a separate work. This scenario is viable for tiny $\lambda$ values of the order of $10^{-6}$ or smaller and
might open up additional windows, as for instance related to LLP searches at the LHC.

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