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Dark matter within the minimal flavour violation ansatz

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ABSTRACT

Minimal Flavour Violation hypothesis can provide an attractive framework for Dark Matter (DM). We consider scalar DM candidates carrying flavour quantum numbers and whose representation under the flavour group guarantees DM stability. They interact with the Standard Model fields through Higgs portal at renormalisable level and also to quarks through dimension-6 operators. We provide a systematic analysis of the viable parameter space for the DM fields, which are triplet of the flavour group, considering several DM-quark interactions. In this framework, we analyse in which cases the viable parameter space differs from Higgs portal models thanks to the underlying flavour structure. In contrast to minimal Higgs portal scenarios, we find that light DM in the GeV mass range as well as heavier candidates above Higgs resonance could be allowed by colliders, direct and indirect DM detection searches as well as flavour constraints. The large mass regime above m_t could even be beyond the reach of future experiments such as Xenon 1T.

1. Introduction

The determination of the nature of DM is one of the main challenges of cosmology and particle physics community today. The Standard Model (SM) of particle physics, despite its great successes along with the likely recent unveiling of its last building block at LHC [1,2], fails in providing a satisfactory DM candidate. In order to characterise the properties of the DM particle, we are forced to go beyond the SM. As of today, no clear scenario for New Physics (NP) is emerging. Concerning DM, we still ignore its intrinsic properties, how it couples to the SM particles and if the dark sector is made of one or several species.

Within the SM, the SM scalar or Brout–Englert–Higgs ("Higgs" for short) boson enjoys a special status since it can allow for a direct coupling to the dark sector at renormalisable level. It is already well known that the so-called "Higgs portal" provides a quite simple and attractive framework for DM phenomenology [3–20]. Interestingly, Higgs searches offer complementary bounds to direct and indirect DM detection searches on the viable parameter space of such DM models, especially in the low mass region [21–23,16, 24–28].

The DM stability requirement is usually ensured by imposing by hand a discrete Z_2 symmetry, under which the DM candidate is odd while the SM fields are even. Several works have however been investigating which models of NP could provide a more fundamental origin for its stability, see e.g. Ref. [29] for a short review. A particular remark should be make on models where more sophisticated global discrete symmetries [30–44] and horizontal gauge symmetries [45–48] have been adopted to deal with the DM phenomenology.

Recently, Ref. [49] sketched the typical features of DM candidates coupling to quarks in a way that is consistent with the Minimal Flavour Violation (MFV) ansatz [50,51]. Interestingly, the MFV, originally motivated to suppress dangerous flavour changing neutral current (FCNC) processes in NP contexts, can have a dual purpose guaranteeing the stability of the DM.

MFV is a working context that has been codified in Refs. [52–59] as a general framework built upon the flavour symmetry of the kinetic terms of the SM Lagrangian. Focusing on the quark sector only, the latter presents a global flavour symmetry whose non-Abelian part is given by

$$G_f = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}. \tag{1}$$

G_f is only broken by the Yukawa interactions, unless the Yukawa matrices are promoted to be auxiliary fields, called spurions, transforming non-trivially under G_f. Without entering into details of a specific NP scenario, generic effects of flavour and CP violation can be described by means of an effective Lagrangian. If all the

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effective operators of this Lagrangian are constructed by means of the SM fields and the Yukawa spurions, all the flavour bounds are satisfied with a NP scale of few TeV [52–54,60,61,55,62,63,58,64–67].

A stable DM candidate can arise within the MFV context when the DM is assumed to carry flavour quantum numbers (see also Refs. [68–70]) and the DM field representation under G_f is chosen in order to prevent DM decay into SM particles. Following the approach of Ref. [49], we assume that the DM fields are neutral under the SM gauge group, but transforms under G_f. For simplicity, we consider new scalar degrees of freedom as DM candidates with the lowest representation under G_f that guarantees their stability. By construction, the DM flavour-multiplets do not couple at the renormalisable level to quarks. Their interactions with SM particles result from the interplay between Higgs portal interactions and effective dimensions-six operators coupling DM to quarks. Notice that Ref. [49] proposed the rules for stable flavoured DM. In that Letter, the DM analysis focused on scalar DM interacting through one particular $d = 6$ operator and with a fixed hierarchy in the DM components. The authors provided a survey of the typical bounds that have to be taken into account from DM and flavour physics. This study missed though several new features in the DM viable parameter space that distinguish the DM within the MFV context compared to the standard Higgs portal DM scenarios.

In this Letter, our purpose is to perform a systematic analysis of the viable parameter space of such DM context and to study how it differs from the simple singlet scalar DM interacting via Higgs portal. In particular, we obtain new features in the few GeV mass range, thanks to DM coannihilation induced by flavour symmetry, as well as larger viable parameter space for the DM mass range above the top mass $m_{DM} > m_t$, when an extra interaction to u-type quarks is considered.

In the following, we first briefly summarise in Section 2 the MFV context and its extension involving a potential DM candidate. In Section 3, we review the general form of effective $d = 6$ operators providing DM-quark interactions compatible with the flavour symmetry. In Section 4, we study the parameter space of this DM scenario considering bounds from direct and indirect DM and collider searches and flavour constraints, and conclude in Section 5.

2. The MFV–DM context

Deviations from the SM predictions induced by NP with generic flavour structure are already severely constrained by the increasing accuracy in the determination of the CKM matrix elements, the measurement of a large number of FCNC processes and of CP asymmetries. In a general context, the scale of NP responsible for the flavour interactions should be above hundreds or thousands TeV [71]. On the other hand, under the MFV hypothesis which prescribes that all the sources of flavour and CP violation in any NP scenario are the same as in the SM, the scale of NP responsible for the flavour interactions is lowered down to few TeV.

This is technically implemented by constructing effective operators describing flavour and CP violation by means of quarks and Yukawa spurions, that transform under the flavour group G_f in Eq. (1). The $SU(2)_L$ doublet Q_L and singlets u_R and d_R transform according to

$$Q_L \sim (\mathbf{3}, \mathbf{1}, \mathbf{1}), \qquad u_R \sim (\mathbf{1}, \mathbf{3}, \mathbf{1}), \qquad d_R \sim (\mathbf{1}, \mathbf{1}, \mathbf{3}), \tag{2}$$

while the Yukawa spurions transform as

$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), \qquad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}), \tag{3}$$

ensuring the invariance under G_f of the Yukawa Lagrangian,

$$\mathscr{L}_Y = -\bar{Q}_L \tilde{H} Y_u u_R - \bar{Q}_L H Y_d d_R + \text{h.c.} \tag{4}$$

Quark masses and mixings are then correctly reproduced (but not predicted [57]) once these spurion fields get background values as

$$Y_u = \mathbf{y}_u, \qquad Y_d = V \mathbf{y}_d, \tag{5}$$

where $\mathbf{y}_{u,d}$ are diagonal matrices whose elements are the Yukawa eigenvalues, and V is the CKM matrix.

Stable DM candidates can be found within the MFV framework looking for the representations of G_f that forbid the construction of operators inducing the DM decay into SM degrees of freedom. It has been shown [49] that the lowest representation under G_f providing a stable DM candidate is a triplet under one of the $SU(3)_i$ composing G_f. The DM stability is then insured for any Lorentz representation of the DM candidate. For definiteness, we consider scalar DM S, neutral under the SM gauge group, and focus on the representation

$$S \sim (\mathbf{3}, \mathbf{1}, \mathbf{1}) \tag{6}$$

under G_f. Let us emphasise that our conclusions on the DM phenomenology should apply to any scalar triplet under one $SU(3)_i$ term of G_f, after a slight modification of the dimension-6 operators that drive its interactions to the quarks (see Section 3).

The low-energy effective Lagrangian describing our setup is given by

$$\mathscr{L} = \mathscr{L}_{SM} + \partial^\mu S^\dagger \partial_\mu S - V(S, H) + \mathscr{L}^f_{\text{eff}} + \mathscr{L}^{DM}_{\text{eff}}, \tag{7}$$

where $\mathscr{L}_{SM}$ is the SM Lagrangian, V is the scalar potential involving the DM field S and the Higgs doublet H. $\mathscr{L}^f_{\text{eff}}$ could contain $d = 6$ pure-flavour operators, described in e.g. Ref. [52], that are suppressed by Λ_f^2, while $\mathscr{L}^{DM}_{\text{eff}}$ contains $d = 6$ DM-flavour operators suppressed by Λ_{DM}^2. Λ_f and Λ_{DM} are the characteristic mass scales of the messengers of the pure-flavour and DM-flavour interactions, respectively, and can a priori be distinct. While Λ_f should be larger than a few TeV [52] to satisfy all flavour constraints, lower values of Λ_{DM} are still allowed. In practice, we do not explicitly include the contribution of $\mathscr{L}^f_{\text{eff}}$ for the numerical analysis in Section 4.3, as $\mathscr{L}^f_{\text{eff}}$ is not expected to affect the DM phenomenology given that in our analysis Λ_f is always larger than Λ_{DM}.

The SM scalar potential get modified at the renormalisable level by the introduction of new scalar degrees of freedom. As already described in Ref. [49], in the MFV context, the new contributions to the scalar potential V read

$$\begin{aligned} V \supset\ & m_S^2 S_i^* \big(a \mathbf{1}_{ij} + b \big(Y_u Y_u^\dagger\big)_{ij} + \cdots\big) S_j \\ & + \lambda S_i^* \big(a' \mathbf{1}_{ij} + b' \big(Y_u Y_u^\dagger\big)_{ij} + \cdots\big) S_j H^\dagger H, \end{aligned} \tag{8}$$

where i, j are flavour indices, a, b, a', b' are dimensionless $\mathcal{O}(1)$ parameters and the ellipsis denotes further negligible[1] Y_d spurion insertions. After flavour and electroweak symmetry breaking (EWSB), $\langle H \rangle = \text{v}/\sqrt{2}$ with $\text{v} = 246$ GeV, the S mass-squared matrix is diagonal and given by

$$\mathscr{L}_m \supset -S_i^* \big[m_A^2 + m_B^2 \mathbf{y}_{u_i}^2\big] S_i, \tag{9}$$

where we have defined

$$m_A^2 = m_S^2 a + \frac{1}{2}\lambda \text{v}^2 a', \qquad m_B^2 = m_S^2 b + \frac{1}{2}\lambda \text{v}^2 b'. \tag{10}$$

[1] Here we follow the common practice considering all interactions up to the first power in $Y_u Y_u^\dagger$. See e.g. Ref. [61] for an analysis studying the impact of resuming over the Yukawa coupling expansion in the context of MFV in the absence of DM.

Of phenomenological importance are the trilinear couplings of the DM particles to the physical Higgs h, which in the mass eigenbasis read:

$$\mathscr{L} \supset -\frac{1}{2}\lambda v h S_i^* \left(a' + b' \mathbf{y}_{u_i}^2\right) S_i \equiv -\frac{1}{2}\lambda_i v h S_i^* S_i, \tag{11}$$

where $\lambda_i \equiv \lambda(a' + b'\mathbf{y}_{u_i}^2)$.

3. The DM-flavour operators

S transforming as a triplet of G_f as in Eq. (6) prevents the construction of any operator containing a single DM field and quarks. A coupling between pairs of DM multiplets and quarks is still allowed through non-renormalisable interactions suppressed by Λ_{DM}^2. When the flavour symmetry G_f and the EW symmetry are unbroken, one can consider the following $d = 6$ operators:

$$\mathscr{L}_{\text{eff}}^{DM} = \frac{1}{\Lambda_{DM}^2} \sum_{\alpha=1}^{5} c_{ijk\ell}^{\alpha} (\mathcal{O}_\alpha)_{ijk\ell}, \tag{12}$$

with

$$(\mathcal{O}_1)_{ijk\ell} = \left(\bar{Q}_{L_i} \gamma^\mu Q_{L_j}\right)\left(S_k^* \overleftrightarrow{\partial_\mu} S_\ell\right), \tag{13}$$

$$(\mathcal{O}_2)_{ijk\ell} = \left(\bar{u}_{R_i} \gamma^\mu u_{R_j}\right)\left(S_k^* \overleftrightarrow{\partial_\mu} S_\ell\right), \tag{14}$$

$$(\mathcal{O}_3)_{ijk\ell} = \left(\bar{d}_{R_i} \gamma^\mu d_{R_j}\right)\left(S_k^* \overleftrightarrow{\partial_\mu} S_\ell\right), \tag{15}$$

$$(\mathcal{O}_4)_{ijk\ell} = (\bar{Q}_{L_i} u_{R_j})\left(S_k^* S_\ell\right)\tilde{H} + \text{h.c.}, \tag{16}$$

$$(\mathcal{O}_5)_{ijk\ell} = (\bar{Q}_{L_i} d_{R_j})\left(S_k^* S_\ell\right) H + \text{h.c.}, \tag{17}$$

where i, j, k, ℓ are flavour indices (see also Refs. [72,73]). The operators above correspond to an effective theory description of the NP sector giving rise to an additional sources of quark-DM coupling besides the Higgs portal interactions. The coefficients $c_{ijk\ell}^{\alpha}$ take into account all possible flavour contractions and read as

$$\begin{aligned} c_{ijk\ell}^1 &= c_1^1 \mathbf{1}_{ij} \mathbf{1}_{k\ell} + c_2^1 \mathbf{1}_{i\ell} \mathbf{1}_{kj} + c_3^1 \left(Y_u Y_u^\dagger\right)_{ij} \mathbf{1}_{k\ell} \\ &\quad + c_4^1 \mathbf{1}_{ij} \left(Y_u Y_u^\dagger\right)_{k\ell} + c_5^1 \left(Y_u Y_u^\dagger\right)_{i\ell} \mathbf{1}_{kj} + \cdots, \end{aligned} \tag{18}$$

$$\begin{aligned} c_{ijk\ell}^2 &= c_1^2 \mathbf{1}_{ij} \mathbf{1}_{k\ell} + c_2^2 \left(Y_u^\dagger Y_u\right)_{ij} \mathbf{1}_{k\ell} \\ &\quad + c_3^2 \mathbf{1}_{ij} \left(Y_u Y_u^\dagger\right)_{k\ell} + c_4^2 \left(Y_u^\dagger\right)_{i\ell} (Y_u)_{kj} + \cdots, \end{aligned} \tag{19}$$

$$\begin{aligned} c_{ijk\ell}^3 &= c_1^3 \mathbf{1}_{ij} \mathbf{1}_{k\ell} + c_2^3 \left(Y_d^\dagger Y_d\right)_{ij} \mathbf{1}_{k\ell} \\ &\quad + c_3^3 \mathbf{1}_{ij} \left(Y_u Y_u^\dagger\right)_{k\ell} + c_4^3 \left(Y_d^\dagger\right)_{i\ell} (Y_d)_{kj} + \cdots, \end{aligned} \tag{20}$$

$$\begin{aligned} c_{ijk\ell}^4 &= c_1^4 (Y_u)_{ij} \mathbf{1}_{k\ell} + c_2^4 \mathbf{1}_{i\ell} (Y_u)_{kj} \\ &\quad + c_3^4 (Y_u)_{ij} \left(Y_u Y_u^\dagger\right)_{k\ell} + c_4^4 \left(Y_u Y_u^\dagger\right)_{i\ell} (Y_u)_{kj} + \cdots, \end{aligned} \tag{21}$$

$$\begin{aligned} c_{ijk\ell}^5 &= c_1^5 (Y_d)_{ij} \mathbf{1}_{k\ell} + c_2^5 \mathbf{1}_{i\ell} (Y_d)_{kj} \\ &\quad + c_3^5 (Y_d)_{ij} \left(Y_u Y_u^\dagger\right)_{k\ell} + c_4^5 \left(Y_u Y_u^\dagger\right)_{i\ell} (Y_d)_{kj} + \cdots, \end{aligned} \tag{22}$$

where we have considered all possible terms up to first powers in $Y_u Y_u^\dagger$ and the dots refer to negligible contractions associated to Y_d insertions. In the following, we use real coefficients c_a^α, according to the MFV ansatz under which all the sources of flavour and CP violation should be associated to the Yukawas only.

The scale Λ_{DM} in Eq. (12) corresponds to a function of couplings and mediator masses whose exact combination depends on the UV completion of the effective theory under study. In principle, different operators or flavour contractions can depend on different type of messengers. $\mathcal{O}_{1,2,3}$ would for instance be the result of a vector boson exchange, while $\mathcal{O}_{4,5}$ would be due to the exchange of scalar or fermionic mediators. Here we assume that the structure of Eqs. (12)–(22) captures the DM phenomenology as long as the DM mass is lighter than the particles mediating the interactions.

Also notice that when the energy scale involved in the physical processes is below the EWSB scale, both the gauge $SU(2)_L \times U(1)_Y$ and the flavour G_f symmetry descriptions used in the definition of Eqs. (13)–(17) break down. One could then wonder for the appearance of new kind of operators, especially for those inducing DM decay, but this is not the case: the effective theory at low energy must match the theory at higher energies and therefore no new gauge or flavour couplings appear.

4. The viable parameter space

In this section, we study the viable parameter space for DM analysing the impact of each dimension-6 operator $\mathcal{O}_{1,\ldots,5}$ on DM phenomenology.

4.1. Constraints from DM and flavour physics

Let us first summarise the constraints that have been imposed in each scenarios. We consider that $\lambda_i < \pi$ in order to preserve a perturbative regime. We take $\lambda_i > -\sqrt{\pi \lambda_h}$, where λ_h is the Higgs self-coupling, to ensure that the scalar potential is bounded from below, assuming that the DM scalar self-couplings are up to $\sim \mathcal{O}(\pi)$. We also impose that $\Lambda_{DM} > m_{S_1}, m_{S_2}, m_{S_3}$ to avoid breaking down of the effective field theory description. In addition, from DM and flavour physics, we have to take into account the following points:

1. *Relic abundance* Ω_{DM}: The total DM abundance deduced from cosmological observations constrains the thermally averaged effective annihilation cross-section $\langle \sigma v \rangle$. In the simplest cases [74], for the Taylor expanded annihilation cross section times the centre of mass velocity $\sigma v = a + b v^2$, the Boltzmann equations for the evolution of DM number density gives rise to the relation

$$\Omega_{DM} h^2 = \frac{1.7 \times 10^9 x_f \ \text{GeV}^{-1}}{\sqrt{g_*}(a + 3b/x_f) m_{pl}} \tag{23}$$

where h is the Hubble parameter,[2] x_f is the ratio between the DM mass and its freeze out temperature, g_* is the number of relativistic degrees of freedom and $m_{pl} = 1.22 \times 10^{19}$ GeV is the Planck mass. The constraint $\Omega_{DM} h^2 \sim 0.1$ [75] translates then into $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3/s$ or equivalently $\langle \sigma v \rangle \sim 3 \times 10^{-9}$ GeV^{-2}. In our numerical analysis of Section 4.2, we use the code `MicrOMEGAs` [76,77] that integrates more accurately the set of Boltzmann equations and we impose $0.09 < \Omega_{DM} h^2 < 0.13$.

2. *Direct and indirect detection*: Direct detection searches are among the best test of Weakly Interacting Massive Particle (WIMP) DM scenarios. This is especially the case of spin independent DM-proton scattering and for masses around 50 GeV. The associated cross-section $\sigma_{DM\,p}$ should be below the bounds of experiments such as PICASSO [78] and Xenon 100 [79] for m_{DM} in the GeV–TeV range. Notice that such experiments have an energy threshold in the few GeV range and PICASSO's threshold is among the lowest ones.
Indirect detection searches are also digging into the viable WIMP mass range. The annihilation cross-section times centre

[2] Here, we keep the notation h for the Hubble parameter as it is widely used in the literature. It should not be confused with the physical Higgs field.

of mass velocity σv, can be tested by FERMI experiment [80]. The Cosmic Microwave Background (CMB) observation experiments such as WMAP [75], SPT [81] and Planck [82] (in the very near future) provide complementary constraints on σv. Indeed, the energy released into the Inter Galactic Medium (IGM) by DM annihilation can alter the thermal history of the Universe, leading to observable changes in CMB observables, see [83–86] and [87,88] for the latest analysis.

3. *Colliders*: Assuming that the particle resonance with a mass of about 125 GeV observed by the ATLAS and CMS Collaborations at the LHC [1,2] corresponds to the Higgs boson, one can constrain the invisible branching ratio to be $\mathrm{Br}(h \to \mathrm{inv}) < 0.15$ at 2σ level [89]. Latest constraints from monojet events observed by the CMS [90] and ATLAS [91] Collaborations can give rise to stringent bounds on $\sigma_{DM\,p}$ complementary to direct detection searches for WIMP masses in the GeV range [92,93]. Let us emphasise that the limits were derived for fermionic DM and in the case of scalar DM these bounds are not always that constraining. In the following, we use the results presented in Ref. [94].
4. *Meson decays*: The bounds on meson decays into invisible final state (see e.g. Ref. [73] for a review) strongly limit the direct couplings of quarks, apart from the top,[3] to the DM. In order to pass these constraints, one has to impose that Λ_{DM} is larger than hundreds of GeV for low mass DM. Dimension-6 operators with such a large scale of NP cannot guarantee the right DM relic abundance. Combining such bounds with the necessary small couplings λ to avoid large Higgs invisible decay width, a DM particle coupling mainly to u-type and d-type quarks through $\mathcal{O}_{1,\ldots,5}$ with mass $m_{DM} < m_D/2$ and $m_{DM} < m_B/2$, respectively, is then excluded.
5. *Meson oscillations*: Since no tree-level diagrams mediated by DM particles can be drawn, contributions to meson oscillations appear only at the loop level, as in the SM. The operators $\mathcal{O}_{1,2,3}$ give negligible contributions to the meson oscillation observables: the MFV ansatz ensures that the GIM mechanism also holds for these loop diagrams; an additional suppression $\propto 1/\Lambda_{DM}^4$ makes NP contributions smaller than the corresponding SM ones. In contrast, the operators $\mathcal{O}_4$ and $\mathcal{O}_5$ have a LR chiral structure and the corresponding contributions to the meson oscillations are chiral enhanced. Following Ref. [49], the Wilson coefficients of the effective interactions $(\bar{q}_{R_i} q_{L_j})(\bar{q}_{R_i} q_{L_j})$, for $i > j$, depend on

$$C_{RL}^{ij} \propto \frac{m_{q_i}^2}{32\pi^2 \Lambda_{DM}^4} \left(V_{tj}^* V_{tj}\right)^2 F\left(\frac{m_{S_h}^2}{m_{S_l}^2}\right), \tag{24}$$

where $m_{S_h}(m_{S_l})$ is the heaviest (lightest) of the S components and $F(x) = ((x+1)\log x)/(x-1) - 2$ is the Inami–Lin function that vanishes in the limit $x \to 1$. For $\Lambda_{DM} \geqslant \mathrm{v}$, these NP contributions can be neglected while for $\Lambda_{DM} \ll \mathrm{v}$, they can be large. Notice that for K meson system, the Wilson coefficients are suppressed by m_s^2/Λ_{DM}^2 and no sizable effects can be seen in ΔM_K and ϵ_K (see Ref. [95] for a recent review for details on the meson oscillation observables). Let us also mention that for B_d and B_s systems, we expect new contributions in ΔM_{B_d} and ΔM_{B_s} only. Indeed, the absence of NP phases, in agreement with the MFV ansatz, prevents modifications on $S_{\psi K_S}$ and $S_{\psi\phi}$. In addition, let us stress that when the DM components are very near in mass the Wilson coefficient get an extra suppression through the Inami–Lin function. This is typically the case when the DM relic abundance is driven by coannihilations.

For the models considered in this Letter, only the DM-quark interactions through $\mathcal{O}_{4,5}$ can thus contribute substantially to meson oscillations. In principle, the operator $\mathcal{O}_4$ can give rise to non-negligible contributions in $\bar{D}^0 - D^0$ oscillations. The large theoretical uncertainties in the D meson system prevents though to set relevant bounds on $\mathcal{O}_4$ mediated interactions. This is not the case in B meson systems. In the presence of $\mathcal{O}_5$ interactions, we impose that NP contributions from (24) are at most equal to the theoretical uncertainties on ΔM_{B_d} and ΔM_{B_s}, i.e. $\Delta C^{ij} = C_{RL}^{ij}/C_{SM}^{ij} \leqslant 0.1$.

Let us also mention that, the operators $\mathcal{O}_4$ and $\mathcal{O}_5$ induce also modifications of the quark mass terms, when contracting the two DM legs at loop to draw a tadpole diagram: these contributions can be safely neglected, providing relative corrections suppressed by loop factors and by m_{DM}^2/Λ_{DM}^2.

4.2. Analytical insights

As previously discussed, the Lorentz structure of the operators $\mathcal{O}_{1,\ldots,5}$ can be categorised into two subgroups. The operators $\mathcal{O}_{1,2,3}$ could arise from vector boson exchange, while operators $\mathcal{O}_{4,5}$ would be associated to fermion or scalar exchange. At this point, it is instructive to analyse the scale of NP Λ_{DM} that would a priori be necessary in order to give rise to the right relic abundance assuming a negligible contribution from Higgs portal. This is particularly relevant for DM masses below the Higgs resonance, where the bounds on the decay width of Higgs into invisible final state strongly constrains the DM-Higgs couplings λ_i (see the colliders section in Section 4.1).

In the limit of low centre of mass velocity, $v \to 0$, the annihilation cross-sections associated to the processes $S_i^* S_i \to \bar{q}_j q_j$ for a fixed value of i and j become at leading order in v:

$$\sigma v|_{\mathcal{O}_{1,2,3}} \simeq \frac{N_c c^2 v^2}{48\pi \Lambda_{DM}^4} \frac{m_q^4 - 5m_q^2 m_{DM}^2 + 4m_{DM}^4}{m_{DM}^2 (1 - m_q^2/m_{DM}^2)^{1/2}},$$

$$\sigma v|_{\mathcal{O}_{4,5}} \simeq \frac{N_c c'^2 m_q^2}{4\pi \Lambda_{DM}^4} \left(1 - m_q^2/m_{DM}^2\right)^{3/2} \tag{25}$$

where N_c is the number of colours of the final state quark, c, c' are a combination of $\mathcal{O}(1)$ coefficients and m_{DM} and m_q are the masses of S_i and q_j respectively. The first cross-section is p-wave suppressed while the second one corresponds to a s-wave driven process. Eq. (23) implies that for e.g. $m_{DM} = 50$ GeV, Λ_{DM} should be ~ 450 GeV for $\mathcal{O}_1$ (five families of quarks are involved) and ~ 200 GeV for $\mathcal{O}_5$ (mainly b quarks involved) in order to get the right relic abundance through annihilation only driven by the dimension-6 operators. Let us emphasise though that given the velocity dependence of the σv's above, it is clear that prospects for indirect detection, involving velocities $v \sim 10^{-3}$, will a priori be more constraining for $\mathcal{O}_{4,5}$ than $\mathcal{O}_{1,2,3}$. In practice, the coannihilations and Higgs portal interactions complicate the relic density analysis. The latter processes are fully taken into account in our numerical treatment of the DM models with the `MicrOMEGAs` code after having introduced the proper Feynman rules using the `LanHEP` package [96]. We have also used `MicrOMEGAs`'s tools for the calculation of the cross-sections relevant for direct and indirect detection searches.

[3] In Ref. [70] it was argued that single top production at LHC with large missing transverse energy involving flavour violating interactions can give rise to novel signature for DM detection. Notice though that for the DM models studied here, the t quarks only decay to u and c quarks and up to now LHC experiments can still not distinguish among light quarks jets.

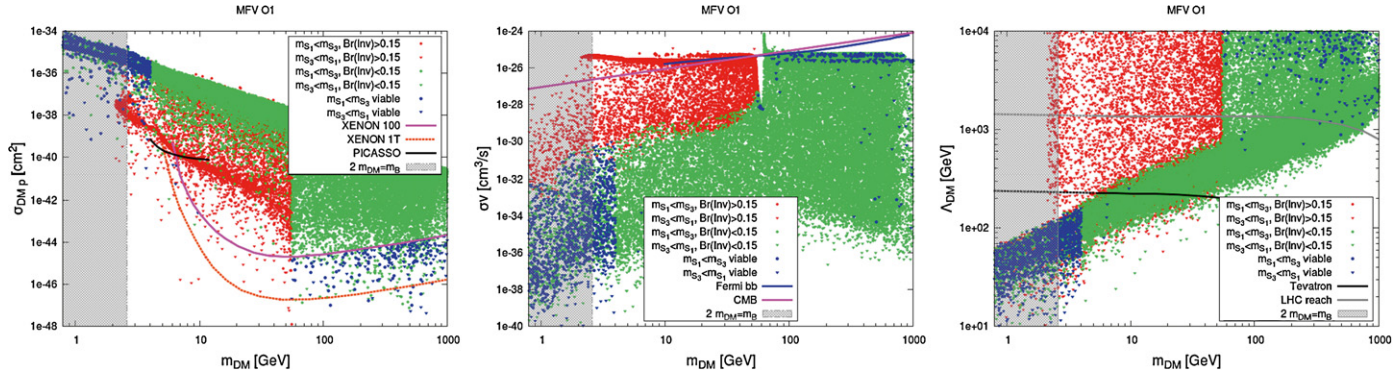

Fig. 1. Operator $\mathcal{O}_1$. Left: DM proton scattering cross-section as a function of the DM mass. Centre: Annihilation cross-section as a function of the DM mass. Right: Scale of NP as a function of the DM mass. In all figures, the red points are excluded by the constraint on the Higgs invisible decay branching ratio, while blue (green) points (do not) pass the direct and indirect detection searches bounds. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

4.3. Numerical analysis

We have performed a random scan of the viable parameter space for DM within the following parameter ranges:

$$0.3 < \left|a, a', b, b', c_a^\alpha\right| < 1.3,$$
$$0.1\ \text{GeV} < m_{S_3} < 1\ \text{TeV},$$
$$m_{DM} < \Lambda_{DM} < 10\ \text{TeV},$$
$$10^{-5} < |\lambda| < \pi \tag{26}$$

considering real, positive and negative values for the parameters a, a', b, b', c_a^α and λ. Let us emphasise that once the value of m_{S_3} is fixed, one can obtain larger or smaller values of m_{S_1} and m_{S_2} by scanning over a, a', b, b' and λ parameters. As a result, in contrast to Ref. [49], we have not imposed in our analysis that S_3 is the lightest component of the S triplet. The constraints from perturbativity, stability of the scalar potential, validity of the effective theory, and DM relic abundance are applied during the scan (see Section 4.1 for more details).

In Figs. 1 and 2, we present the results of the scans for the operators $\mathcal{O}_1$ and $\mathcal{O}_{4,5}$ in the planes m_{DM}–$\sigma_{DM\,p}$, m_{DM}–σv and m_{DM}–Λ_{DM} superimposing the constraints from direct, indirect and colliders searches respectively. The corresponding plots for operators $\mathcal{O}_{2,3}$ are very similar to the ones for $\mathcal{O}_1$. The red points are excluded by constraints on the invisible decay branching ratio of 125 GeV Higgs, while the blue (green) points (do not) pass the constraints from the combined PICASSO, Xenon 100, FERMI and CMB experiments.

Notice that in the m_{DM}–σv plots, we only show the constraint from FERMI on annihilation into $\bar{b}b$ at 100% as they are the most limiting in the model under study. The limit associated to CMB represented in the plots results from the analysis of Ref. [87]. The latter makes use of the recent SPT data assuming a value of the fraction of released energy in the IGM of 0.2 which should be representative of DM annihilating to quarks.[4] In the legend of the plots, the "viable" reference should be interpreted as "passes direct, indirect detection and CMB constraints". In the m_{DM}–$\sigma_{DM\,p}$, we also present the reach of the future Xenon 1T experiment [97] that will test most of the large mass regime of $\mathcal{O}_{1,\ldots,5}$ operators.

[4] Notice that a similar analysis [88] shows the expected limits for each annihilation channels for WMAP7 and future Planck data release. It appears that the limits do not vary much going from annihilations into quarks to annihilation into gauge or Higgs boson. Also notice that Ref. [88] obtain a slightly less constraining bound for future Planck data. Here we stay a bit more conservative using the results of Ref. [87].

We will see that some blue points do not pass monojet searches constraints from Tevatron or are within the reach of LHC at $\sqrt{s} = 14$ TeV. In Figs. 1 and 2, we represent with dotted lines the continuation of the limits from Ref. [94] to masses $m_{DM} < 5$ GeV. Notice however that in Ref. [94] slightly different assumptions were made on the coupling of DM to quarks compared to the present analysis. The lines in the $m_{DM} - \Lambda_{DM}$ associated to Tevatron and LHC constraints are thus mainly a guide for the eye. We thrust though that $\mathcal{O}_{1,2,3}$ low mass candidates are already excluded by such analysis (see Fig. 1), while for $\mathcal{O}_{4,5}$ only a few models are within the reach of LHC. A more detailed analysis of LHC prospects for detection of such a DM candidate is however beyond the scope of the present Letter.

4.3.1. General features

Several features appear in Figs. 1 and 2. Let us first concentrate on the $\sigma v - m_{DM}$ plots. Typically, when the correct relic abundance is achieved and it is driven by annihilation processes, the annihilation cross-section today reaches $\sim 3 \times 10^{-26}$ cm^3/s. In this σv range, we clearly see two preferred values of the annihilation cross-sections, especially in Fig. 2. The annihilation cross-section for $S_{1,2}$ DM today appears to be typically twice as large as the one for S_3.

This can be understood considering the fact that, in the MFV context, S_1 and S_2 are generally quite degenerate, see Section 2. In the latter case, the effective DM annihilation cross-section [74] driving the relic abundance goes as $\langle \sigma v \rangle \sim (\sigma v_{11} + \sigma v_{12} + \sigma v_{21} + \sigma v_{22})/4$ where σv_{ij} refers to the cross-sections times velocity associated to $S_i S_j^* \to X$ annihilation and coannihilation processes (X is a SM final state) in the $v \to 0$ limit, assuming that the relic abundance is driven by s-wave dominated processes. When coannihilation processes are suppressed, i.e. $\sigma v_{ij\,i\neq j} \ll \sigma v_{ii}$ and σv_{ii} is identical for $i = 1, 2$, we get $\langle \sigma v \rangle = \sigma v_{11}/2 \sim 3 \times 10^{-26}$ cm^3/s. This is what we observe in e.g. the upper plot of Fig. 2 when Λ_{DM} is large and more especially when the interactions driven by c_2^α terms in Eqs. (21)–(22) are suppressed. Notice that we apply the detection searches constraints as if all the DM in the galaxies was made of only one species S_i. This is a rather conservative approach. If we had to consider that half of the DM is made of e.g. S_1 and the other half of S_2, some extra models with $m_{S_1} < m_{S_3}$ could be considered as viable.

Also notice that an important change in the number of relativistic degrees of freedom g_* (from ~ 100 to ~ 10, see e.g. Ref. [98]) occurs in the early universe around[5] $T_{QCD} \sim 150$ MeV due to the

[5] A $T_{QCD} \sim 150$ MeV has been taken into account in `MicrOMEGAS` code.

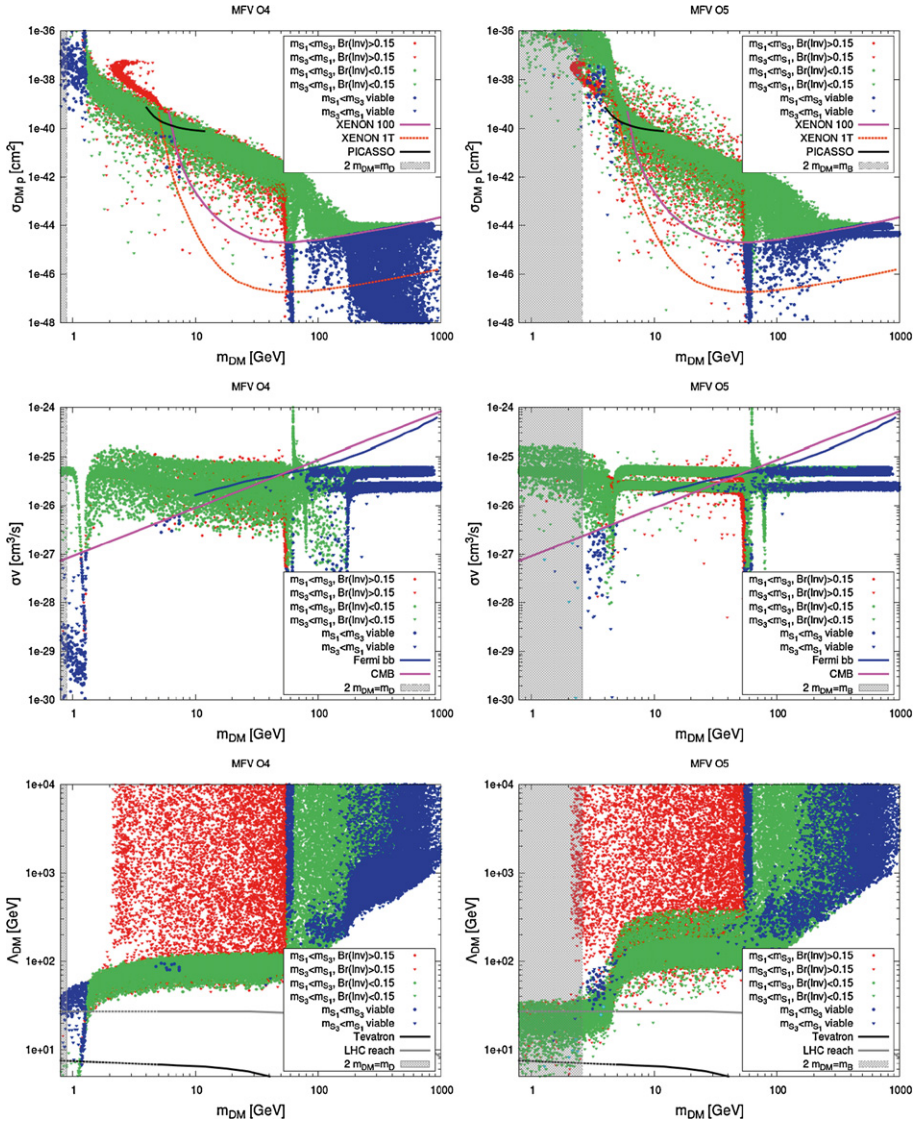

Fig. 2. Operators $\mathcal{O}_4$ (left) and $\mathcal{O}_5$ (right). Top: DM proton scattering cross-section as a function of the DM mass. Centre: Annihilation cross-section as a function of the DM mass. Bottom: Scale of new physics as a function of the DM mass. In all figures, the red points are excluded by the constraint on the Higgs decay invisible branching ratio, while blue (green) points (do not) pass the direct and indirect detection searches bounds. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

QCD phase transition. This implies larger values of the annihilation cross-section for $m_{DM} \sim T_{QCD} x_f$.

The relative absence of points in the $m_{DM} \sim m_h/2$ is due to resonant DM annihilation through Higgs exchange. This feature is also well visible in the Λ_{DM}–m_{DM} and $\sigma_{DM\,p}$–m_{DM} plots. Another dip appears in all cases at $m_{DM} \sim m_W$ when the annihilation into gauge bosons through Higgs exchange become kinematically available. The other dips specific to the form of each operators are discussed in the following.

Considering now the Λ_{DM}–m_{DM}, we see that above the Higgs resonance the value of the Λ_{DM} does not play an important role given that any value above 100 GeV is allowed by all the constraints. Below the Higgs resonance, Λ_{DM} should be typically smaller than $\mathcal{O}(100)$ GeV to account for the DM relic abundance together with small contributions from the Higgs portal to evade a large correction to the Higgs width. Let us also remind that flavour observables, mainly meson decays into DM particles, impose that Λ_{DM} is larger than hundreds of GeV for m_{DM} in the GeV range [73]. More precisely, this constraint rules out $m_{DM} < m_D/2$ and $m_{DM} < m_B/2$ for the operators $\mathcal{O}_4$ and $\mathcal{O}_{1,5}$, respectively and the excluded regions are represented as (grey) shaded areas in Figs. 1 and 2. Moreover, the meson oscillation tends to constrain $\Delta C^{ij} < 0.1$, see Section 4.1. This threatens the DM models of $\mathcal{O}_5$ with the lowest values of Λ_{DM}. The few points that are eventually excluded by this constraint are represented in light blue colours in the plots of the right column of Fig. 2.

The candidates that pass direct and indirect detection searches constraints (dark blue points) appear in two distinct mass ranges: below 10 GeV, where the direct detection bounds are weak, and above $m_h/2$ as in the case of Higgs portal models [16]:

- For masses below 10 GeV, the scale of new physics is below ~ 200 GeV and the processes driving the relic abundance are typically related to the dimension-6 operators $\mathcal{O}_{1,\ldots,5}$.
- Around 60 GeV, near the Higgs resonance, the scale of new physics is typically above 1 TeV and the coupling to the Higgs particle is small ($\lambda < 0.01$).
- Above 60 GeV, the scale of new physics is of several hundreds of GeV and the coupling to the Higgs particle is $\mathcal{O}(0.1 - \pi)$.

4.3.2. Operators $\mathcal{O}_{1,2,3}$

In Fig. 1, we present scatter plots associated to the operator $\mathcal{O}_1$. We have checked that equivalent results for $\mathcal{O}_{2,3}$ can be obtained (up to some $\mathcal{O}(1)$ factor in the Λ_{DM}). Given the p-wave suppression of the annihilation cross-section, see Eq. (25), it is the direct detection searches sector that provides the strongest constraints when $\mathcal{O}_1$ drives the DM relic abundance. In the low mass regime, they are limited by PICASSO's energy threshold at $m_{DM} \sim 4$ GeV. Let us emphasise though that for scalar DM interacting through vector interactions with quarks, it has been shown [94] that monojet searches at Tevatron already provide very strong constraints on GeV range DM masses and rule out all the new potentially viable DM candidates with $m_{DM} < 10$ GeV, as shown in the plot on the right hand side of Fig. 1. For masses just above Higgs resonance, the presence of extra interactions through $\mathcal{O}_1$ allows for lower value of the $\sigma_{DM\,p}$ than in Higgs portal models and viable candidates that could be within the reach of future Xenon 1T experiments and in some rare cases will be tested by LHC at $\sqrt{s} = 14$ TeV.

4.3.3. Operators $\mathcal{O}_{4,5}$

In the case of the $\mathcal{O}_{4,5}$ operators, the results are shown in Fig. 2. This time the annihilation cross-section is an s-wave process so that the indirect detection searches can compete with direct detection bounds for $m_{DM} < 10$–20 GeV. In the m_{DM}–σv plane, in addition to the Higgs and gauge bosons resonances, some other dips appear at $m_{DM} \sim m_c, m_t$ in the $\mathcal{O}_4$ and $m_{DM} \sim m_b$ in the $\mathcal{O}_5$ case. They are due to the fact that the main DM annihilation channels into $S_i^* S_i \to \bar{c}c, \bar{t}t$ and $\bar{b}b$, respectively, are suppressed by factors of $(-m_q^2 + m_{DM}^2)^{1/2}$ in the low velocity limit, see Eq. (25). Away from those dips and resonances, the points getting lower values of the annihilation cross-section have their relic abundance mainly driven by coannihilation processes.

As it can be seen in the bottom plots of Fig. 2, monojets searches [94] are not very limiting in the case of scalar type DM-quarks interactions. The low mass regime appears to pass all constraints in contrast to the case of simple Higgs portal scenarios or to the case of Higgs portal $+\,\mathcal{O}_{1,2,3}$ considered in the previous section.

The particularities of operators $\mathcal{O}_4$ and $\mathcal{O}_5$ are the following:

4.3.3.1. Operator $\mathcal{O}_4$: In the low mass range, viable DM candidates get an extra suppression of their relic abundance due to $S_1 S_2^* \to u\bar{c}$ coannihilation process, driven by the interaction terms proportional to c_2^4 and c_4^4 in Eq. (21). For $m_{1,2} < m_c$, the coannihilation drives the relic density, while for $m_{1,2} > m_c$ it is a combination of coannihilations and $S_2 S_2^* \to c\bar{c}$ that is relevant. Let us remind that in order to get a non-negligible contribution from coannihilations between two particles, their relative mass difference should be $\Delta m/m \sim 0.1$ in order to avoid exponential Boltzmann suppression. In the case of $\mathcal{O}_4$ no particular tuning in $m_{1,2}$ has to be invoked given that their degeneracy is granted thanks to the small u and c quarks Yukawa couplings in Eq. (9).

Also notice that in the case of $\mathcal{O}_4$, for $m_{DM} > m_t$ regime, one can obtain a very reduced value of $\sigma_{DM\,p}$ compared to minimal Higgs portal scenarios (see e.g. [16]). This typically happens in the case of negligible coupling to the Higgs so that $S_i S_i^* \to WW, ZZ, \bar{t}t, hh$ through Higgs exchange are suppressed while $\mathcal{O}_4$ drives the DM relic abundance through $S_i S_i^* \to \bar{t}t$ for $m_{DM} > m_t$. This can be understood qualitatively by comparing the DM-proton scattering cross-sections for Higgs portal and $\mathcal{O}_4$ models. In the first case $\sigma_{DM\,p}^h \propto f_{ph}^2 \lambda_i^2/(m_h^4 m_{DM}^2)\mu^2$ [9] while in the latter case $\sigma_{DM\,p}^{\mathcal{O}_4} \propto f_{p4}^2 c^2/(\Lambda_{DM}^4 m_{DM}^2)\mu^2$ [49] and μ is the DM-proton reduced mass. The nucleon form factors corresponds to $f_{ph} \simeq 0.4$ and $f_{p4} \simeq 0.1$ in the Higgs portal and in the $\mathcal{O}_4$ case, respectively, using the `MicrOMEGAs` default parameters [76]. The differences between f_{ph} and f_{p4} are principally due to the fact that $\mathcal{O}_4$ does not provide a coupling to the s quark. For large DM masses, one can also relates the values of $\sigma v \propto g^2\lambda^2/m_{DM}^2$ and $\sigma v \propto c^2 m_t^2/\Lambda_{DM}^4$ for a DM abundance driven by Higgs portal or $\mathcal{O}_4$ processes, respectively. Eventually we get for $m_{DM} \ll m_t$, a $\sigma_{DM\,p}^{\mathcal{O}_4}$ that is suppressed compared to $\sigma_{DM\,p}^h$ by a factor $(f_{p4}/f_{ph})^2$ and also by a factor $\sim m_h^4/(m_t^2 m_{DM}^2)$.

4.3.3.2. Operator $\mathcal{O}_5$: Below 10 GeV, viable candidates have their relic density mainly driven by coannihilations $S_1 S_3^* \to \bar{b}d$ and $S_2 S_3^* \to \bar{b}s$. All these coannihilation channels are described by the flavour interactions proportional to c_2^5 and c_4^5 in Eq. (22). The $S_{1,2} S_3^*$ coannihilation processes require some tuning of the parameters. Eq. (9) gives rise to $m_1, m_2 \sim |m_A|$ and $m_3 \sim |m_B|$ so that, if $a^{(\prime)}, b^{(\prime)} = +1$, $m_3 \simeq 2m_{1,2}$. Allowing for different signs and the range of parameters in Eq. (26), we can get relative mass differences ~ 0.1 necessary for coannihilation.

From the above analysis appears that the coannihilation channels $S_1 S_2^* \to u\bar{c}$ for $\mathcal{O}_4$ and $S_1 S_3^* \to \bar{b}d$ and $S_2 S_3^* \to \bar{b}s$ for $\mathcal{O}_5$ enable viable DM parameter space in the GeV range. This is due to the flavour interactions driven by c_2^α and c_4^α with $\alpha = 4, 5$ and this feature is absent in standard Higgs portal models. Notice that the GeV mass range will be tested in the next future by direct detection searches experiment, see e.g. Ref. [99] for SuperCDMS. Moreover, in the higher mass regime $m_{DM} > m_t$, $\mathcal{O}_4$ can give rise to rather suppressed DM-nucleon cross-sections that could even evade future Xenon 1T constraints.

5. Conclusions

Embedding the DM problematic within MFV context can guarantee DM stability [49]. In addition, flavour DM-fermions interactions, that naturally arise in this framework, give rise to a richer DM phenomenology than in the minimal Higgs portal scenarios (see e.g. [16] for a recent analysis). In this Letter, we focused on the MFV in the quark sector only with the Yukawas of the quarks being the only sources of flavour and CP violation. For definiteness, we have restricted our analysis to the case of scalar DM fields, neutral under the SM gauge symmetry, but transforming as a triplet under one of the $SU(3)$ composing the flavour symmetry group $G_f = SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$.

In this scenario, DM interacts with the SM fields through Higgs portal at renormalisable level and also to quarks through dimension-6 operators. We have considered three vector operators and two scalar ones. We have performed a systematic analysis of the DM viable parameter space for each of these operators. We have obtained that DM candidates can pass direct and indirect DM detection searches constraints both below 10 GeV and above $m_h/2$.

Complementary constraints from colliders and flavour physics have been taken into account. In general the non-observation of meson decays into invisible final states exclude $m_{DM} < m_D/2$ or $m_{DM} < m_B/2$ mass ranges. In the case of dimension-6 operators with DM-quarks vector like interactions, monojet searches at colliders rule out all the new potentially viable DM candidates with $m_{DM} < 10$ GeV. For what concerns scalar type dimension-6 interactions, monojet searches are less limiting and allow for a viable $m_{DM} < 10$ GeV parameter space that will probably evade future LHC monojet searches. In most cases, it also evades constraints from flavour violating processes such as meson oscillations. In the large mass regime, most of the viable parameter space will be within the reach of future direct detection searches experiments

such as Xenon 1T, apart from the case of DM scalar-type coupling to u-type quarks that can evade the latter bound for $m_{DM} > m_t$.

To summarise, when the DM is embedded in the MFV framework, the DM stability is granted for certain representations of the DM fields under G_f. In this work, we systematically analysed the rich interplay between flavour and DM physics when considering vector and scalar type DM-quark interactions invariant under the original G_f symmetry. Compared with minimal Higgs portal models, DM candidates with $m_{DM} \sim$ GeV range are viable in these scenarios. Furthermore, DM particles with $m_{DM} > m_t$ could even be beyond the reach of future experiments such as Xenon 1T.

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