Impact of ATLAS constraints on effective dark matter-standard model interactions with spin-one mediators

Fabiola Fortuna\(^1\) and Pablo Roig\(^1\)
\(^1\)Centro de Investigación y de Estudios Avanzados, Apartado Postal 14-740, 07000, Ciudad de México, México

Abstract

We complement a previous work \cite{1} using an EFT framework of dark matter and standard model interactions, with spin-one mediators, exploring a wider dark matter mass range, up to 6.4 TeV. We use again bounds from different experiments: relic density, direct detection experiments and indirect detection limits from the search of gamma-ray emissions and positron fluxes. Besides, in this paper we add collider constraints by the ATLAS Collaboration in monojet analysis. Moreover, here we tested our previous results in the light of the aforementioned ATLAS data, which turn out to be the most restrictive for light dark matter masses (as expected), \(m_{\text{DM}} < M_Z/2\). We obtain a larger range of solutions for the operators of dimension 5, OP1 and OP4, where masses above 43 GeV and 30 GeV (but for the \(Z\) resonance region, \(\sim (M_Z \pm \Gamma_Z)/2\)), respectively, are allowed. In contrast, the operator of dimension 6, OP3, has viable solutions for masses \(\gtrsim 190\) GeV. For the combination of OP1&OP3 we obtain solutions (for masses larger than 140 or 325 GeV) that depend on the relative sign between the operators.

1 Introduction

Understanding the fundamental nature of Dark Matter (DM) is one of the most compelling problems in particle physics and cosmology, yet despite years of searching, the identity of DM remains a mystery. A favoured paradigm for the particle nature of dark matter is that of Weakly Interacting Massive Particles (WIMPs) \cite{2–4}. In this scenario the DM interactions with the Standard Model (SM) are sufficiently weak to meet the constraints of direct \cite{5–11} and indirect detection experiments \cite{12–22}, but strong enough to generate the relic abundance inferred from measurements of the cosmic microwave background radiation \cite{23}. In absence of any direct DM signal, the generality of the effective field theory (EFT) approach may be advantageous \cite{24–30}, as it only uses the known SM symmetries and degrees of freedom, assuming that the typical energy of all relevant processes lies below the mediator mass. We will follow such an approach by using an effective Lagrangian to parameterize the interactions of the dark sector with the SM, and determine the restrictions imposed by the experimental/observational constraints. The Higgs portal (see ref. \cite{31} and references therein) and neutrino portal cases \cite{32–48} have received considerably more attention than the case of spin-one mediators, so we will focus on the latter — both in the Proca or antisymmetric tensor representations —.

Here we will continue exploring the phenomenological consequences of the EFT scenario developed in ref. \cite{49} for the interactions between SM and DM particles with heavy mediators. We have already studied the low energy region, with DM masses under \(m_Z/2\) in Ref. \cite{1}. In that analysis, we found solutions complying with the constraints imposed: \(Z\) invisible decay width \cite{50}, relic density \cite{50}, direct detection experiments from Xenon1T \cite{51}, PandaX \cite{52}, LUX \cite{53}, DarkSide-50 \cite{54} and CRESST-III \cite{55}. We also employed indirect detection limits from the search of gamma-ray emissions \cite{56} and positron fluxes \cite{57}. In this work we extend the region of DM masses under analysis, from 50 GeV up to 6.4 TeV (slightly less than half the LHC center-of-mass collision energy, as our DM particles need to be pair-produced, accounting for the detection jet energy threshold). We use again the restrictions mentioned above and we add collider constraints by the ATLAS collaboration \cite{58}. In fact we also tested our previous results from the low energy region against the ATLAS data and further restricted the space of solutions.
The paper is organised as follows: In section 2 we introduce the EFT that we are using [49] and highlight the part interesting for this study and our conventions. Then in section 3 we analyze several observational limits: in subsection 3.1 we check that the observed relic abundance can be reproduced in the different cases, in subsection 3.2 we verify the direct detection bounds are respected; and in subsections 3.3 and 3.4 we consider the indirect bounds given by dwarf spheroidal satellite galaxies and the positron flux, respectively. After that, in section 4 we include the collider constraints by the ATLAS collaboration; finally the discussion and conclusions are presented in section 5.

2 Effective Lagrangian

We study interactions between dark matter and standard model particles using an effective field theory approach, where we consider that the heavy mediators that generate the interaction are of spin one. In the dark sector we can have scalars, Φ, fermions, Ψ, and vectors, X. The mediators are weakly coupled to both sectors, dark and standard, and this information is encoded in the effective coefficients $X_{\text{eff}}$. We assume that the dark fields transform non-trivially under a symmetry group, $G_{\text{DM}}$ (that we do not need to specify), while all SM particles are singlets under this $G_{\text{DM}}$, which ensures the stability of the DM particle. Also, all dark fields are singlets under the SM gauge group. The consequence of interactions generated by a mediator are that our operators have the form:

$$\mathcal{O} = \mathcal{O}_{\text{SM}} \mathcal{O}_{\text{dark}},$$  \hspace{1cm} (1)

and we know that $O_{\text{dark}}$ contains at least two fields because we have assumed that the dark fields transform non-trivially under $G_{\text{DM}}$. In the effective Lagrangian, each term has a factor $1/\Lambda^n$, $n = \text{dim}(\mathcal{O}) - 4$, where $\Lambda$ is of the order of the heavy mediator mass(es). We restricted ourselves to operators of mass dimension $\leq 6$. In this work, we focus on operators with vector and antisymmetric tensor mediators because the models with scalar and fermion mediators have already been studied extensively [25, 28, 41, 59–67].

The Lagrangian we use, is conveniently separated into two parts ($\psi$ stands for SM fermions and $B_{\mu\nu}$ is the $U(1)_Y$ field-strength tensor, universal couplings to the SM fermions are assumed):

- Terms involving dark fermions (Ψ):

$$\mathcal{L}_{\text{eff}}^\Psi = \frac{\tau_{\text{eff}}}{\Lambda} B_{\mu\nu} \bar{\Psi} \sigma^{\mu\nu} \Psi + \frac{A_{\text{eff}}^{L,R}}{\Lambda^2} \bar{\psi} \gamma_\mu \psi \gamma^\mu \gamma_P L,R, \Psi + \frac{\kappa_{L,R}}{\Lambda^2} B_{\mu\nu} \bar{\Psi} \left( \gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu \right) \gamma_P L,R, \Psi. \hspace{1cm} (2)$$

- Terms involving dark bosons (X, Φ):

$$\mathcal{L}_{\text{eff}}^{X,\Phi} = \frac{\zeta_{\text{eff}}}{\Lambda} B_{\mu\nu} X^{\mu\nu} \Phi + \frac{\epsilon_{\text{eff}}}{\Lambda^2} \bar{\psi} \gamma_\mu \psi 1 \Phi \gamma_P L,R, \Psi. \hspace{1cm} (3)$$

3 Observational limits

We use the following notation for our operators $^1$:

$$\begin{align*}
\text{OP1} &\equiv B_{\mu\nu} \bar{\Psi} \sigma^{\mu\nu} \Psi, \\
\text{OP2} &\equiv \bar{\psi} \gamma_\mu \psi \gamma_P L,R, \Psi, \\
\text{OP3} &\equiv B_{\mu\nu} \bar{\Psi} \left( \gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu \right) \gamma_P L,R, \Psi, \\
\text{OP4} &\equiv B_{\mu\nu} X^{\mu\nu} \Phi, \\
\text{OP5} &\equiv \frac{1}{2t} (\bar{\psi} \gamma_\mu \psi) (\Phi \gamma_P L,R, \Phi).
\end{align*} \hspace{1cm} (4)$$

We also consider the combined contributions from dimension 5 and 6 operators when they contain the same DM candidate; in such cases we adopt the following relationship between the scales $\Lambda$ and operator coefficients $C$:

$^1$We note the recent study of ref. [68] using OP4, in the context of feebly coupled vector boson DM.
\[ \Lambda_{\text{dim 6}} = \Lambda_{\text{dim 5}}, \quad C_{\text{dim 6}} = \pm C_{\text{dim 5}}. \] (5)

In most combinations, the relative sign between coefficients is irrelevant, with the exception of the combination between OP1 and OP3, where phenomenology can vary slightly depending on their relative sign.

We are using \( \Lambda = 2m_{\text{DM}} \) when combining operators of different dimensions \( \text{dim} \). We consider that equality a safe limit for the convergence of the effective theory, as discussed in [64]. Also in [69], the authors use the same relationship for their calculations to be meaningful in the EFT framework. Depending on the UV completion of the theory, a possible s-channel process in the high-energy theory might break the EFT when the corresponding heavy mediator resonates. We have checked that our results change insignificantly moving slightly away from the previous equality (\( \Lambda \gtrsim 2m_{\text{DM}} \)). Hereafter, we will be expressing constraints on ratios of effective couplings over \( \Lambda^{(2)} \) as bounds on the couplings by using \( \Lambda = 2m_{\text{DM}} \), for given DM masses. When combining operators, sticking to the case \( \Lambda = 2m_{\text{DM}} \) maximizes the impact of higher-dimensional operators, through their interference with the leading ones, while keeping the convergence of the EFT. Of course solutions can be found for \( \Lambda > 2m_{\text{DM}} \). Indeed, as \( \Lambda/m_{\text{DM}} \) increases, the subleading operators become eventually negligible and the results from the single operators of leading dimension are recovered.

### 3.1 Relic density

We use micrOMEGAs code [70] to compute the relic abundance of dark matter in our EFT. We use the single operator hypothesis, and we obtain the coefficients in the Lagrangian —in eqs. (2) and (3)— such that they reproduce the observed relic density [71]

\[ \Omega_{\text{DM}}h^2 = 0.1200 \pm 0.0012. \] (6)

In the calculations below, we will use the effective couplings that correctly reproduce the relic density, eq. (6).

### 3.2 Direct Detection Experiments

For the mass range that we are studying, the most stringent limits on spin-independent scattering cross sections of DM and nucleons come from the LUX-ZEPLIN experiment [72]. However, we also include limits from the XENON1T [51] and PandaX-4T [73] experiments. Again we use micrOMEGAs [70] to compute the DM-nucleon cross sections within our EFT, in the limit where the relative velocity goes to zero. Fig. 1 shows our results for several operators in our EFT and compares them with the experimental limits. The notation used in this figure is defined in eq. (4). We can see that OP2, OP5 and the combinations of OP1&OP2, OP2&OP3 and OP4&OP5 are completely ruled out by these experiments. Operators not shown in fig. 1 have DM-nucleon cross sections many orders of magnitude below the current experimental limits from direct detection experiments. Therefore, in the following we will only consider those operators not plotted in fig. 1 —OP1, OP3, OP4 and the combination of OP1&OP3—.

### 3.3 Dwarf spheroidal satellite galaxies

Using the first year of data from the Dark Energy Survey (DES), eight new dwarf spheroidal satellite galaxies (dSphs) were discovered recently. The dSphs of the Milky Way are some of the most DM dominated objects known. The dSphs are excellent targets for the indirect detection of DM due to their proximity, high DM content, and apparent absence of non-thermal processes. Analyzing Fermi Large Area Telescope data obtained along six years, Ref. [56] searched for gamma ray emission coincident with the positions of these eight new objects. No significant excess of gamma-ray emission was found. Then, in Ref. [56] they computed individual

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2 Although all operators that we consider in this work can, in principle, be generated at tree level by spin-one mediators neutral under both SM and DM gauge groups [49], a caveat is in order. If the dimension 5 operators are generated at loop level, the ratio \( m_{\text{DM}}/\Lambda \) could be a few orders of magnitude smaller. This would depend on the hierarchy between \( m_{\text{DM}} \) and \( m_{\text{loop}} \) (the mass of the inner particle in the loop, not necessarily the mediator or the DM particle), and that is completely model dependent.

3 A comment on the operator coefficients is pertinent: depending on the working assumptions (neutral or charged mediators under SM and DM gauge groups, mediators’ spin, etc.) a given operator can be generated at tree level or first appears at one loop (see section 2.1. of [49]). If the underlying physics is weakly coupled, the coefficient is suppressed by \( \sim 1/(16\pi^2) \), which may require an unnaturally large dimensionless coupling value, that -on the contrary- would be expected if the underlying physics is strongly coupled.
Figure 1: WIMP cross sections (normalized to a single nucleon) for spin-independent coupling versus mass. The notation in this figure is defined in eq. (4). When we combine operators with the same DM candidate, we use $\Lambda = 2m_{DM}$. Operators not shown here have cross sections many orders of magnitude below the current limits.

and combined limits on the velocity-averaged DM annihilation cross section for these new targets —assuming that the DES candidates are dSphs with DM halo properties similar to the known dSphs—.

Using micrOMEGAs [70], we computed the non-relativistic ($m_{DM} \ll T$) thermally-averaged DM annihilation cross sections $\langle \sigma v \rangle$, using our effective operators —those that are not ruled out by direct detection experiments, see fig. 1—, and compared the results with the limits mentioned above. The results are presented in figure 2, and we can see that these limits do not help us to constrain our mass region. Note that the combination of operators OP1 and OP3 has a relative sign between its coefficients, because the one with the same sign gives velocity-averaged cross sections even below those shown in the figures.

Figure 2: Restrictions from dSphs on the DM annihilation cross sections into (a) $b\bar{b}$, (b) $\tau^+\tau^-$ for the portals generated by several operators, defined in eq. (4). We see in both panels that the entire mass region is allowed by the data.
3.4 Limits from AMS-02 positron measurements

The AMS-02 Collaboration has presented high-quality measurements of positron fluxes as well as the positron fraction. In Ref. [57] the authors used measurements of the positron flux to derive limits on the dark matter annihilation cross section and lifetime for various final states, and extracted strong limits on DM properties. They worked under the well-motivated assumption that a background positron flux exists from spallations of cosmic rays with the interstellar medium and from astrophysical sources. We again computed the DM annihilation cross sections, now into $e^+e^-$ and $\mu^+\mu^-$, using micrOMEGAs [70] and compare them with the bounds derived in Ref. [57]. They also derived limits for the $\tau^+\tau^-$ and $b\bar{b}$ final states, but these are weaker than those from dSphs data. In figure 3 we see that our results are below the experimental limits and we cannot rule out any mass region. Note that in this figure we again show the combinations of OP1 and OP3 with a relative sign between their coefficients, while their combination with the same sign gives even smaller values for the velocity-averaged cross sections.

We refine our calculation of the DM annihilation cross sections done previously in ref. [1] and the region of masses allowed was slightly modified. This change is only noteworthy in the case of the OP4, because the collider constraints exclude masses in the region $m_\psi < m_\pi/2$ for OP1, OP3 and the combinations of OP1 & OP3, as we will see below. The data constraining DM annihilation into the final state $e^+e^-$ is the most stringent, therefore is the one we present here, in fig. 4. We see that masses smaller than $\sim 30$ GeV are ruled out, while masses in the range $[30, 50]$ GeV are allowed.

Figure 3: Restrictions from AMS-02 data on the DM annihilation cross sections into (a) $e^+e^-$ and (b) $\mu^+\mu^-$ for the portals generated by several operators, defined in eq. (4). We see that the entire mass region is allowed by the data. The limits shown as solid lines were derived from sampling over various energy windows, while the dashed lines are from considering those windows including only data with energies above 10 GeV [57].

3.5 Is the EFT perturbative?

We want our EFT to be in the perturbative regime, which imposes an upper limit in the dimensionless effective couplings of eqs. (2) and (3). We bind it using that the corresponding $\alpha = g^2/(4\pi)$, where $g^2$ stands for any coupling in eqs. (2) and (3), should be at most $\sim 1/2$ to keep perturbativity. As before, we took the effective couplings that correctly reproduce the relic abundance. We found that, for the OP4 with $m_X \neq m_\phi$: if the smaller mass is $< 1$ TeV, relationships as $m_X = 3m_\phi$, $m_\phi = 3m_X$ are allowed. While if the smaller mass is 1 TeV $< m < 3.2$ TeV, the other particle can only be twice heavier. The quantities that we obtained for the rest of the operators satisfy this criterion of perturbativity.

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4Before, we used the first two terms of a series expansion of $\langle \sigma v \rangle$ as a function of $x = m/T$, where $m$ stands for the DM mass and $T$ is the temperature. In this work we used micrOMEGAs to compute $\langle \sigma v \rangle$ more accurately (the updated values are shown in fig. 4). This change explains the small difference in the low mass region of OP4, between the results summarized in tables 1 and 2.
Figure 4: Restrictions from AMS-02 data on the DM annihilation cross sections into $e^+e^-$ for the portal generated by OP4, defined in eq. (4). This plot tests the mass region $m_\psi < m_Z/2$, and we see that masses larger than $\sim 30$ GeV are allowed.

4 Collider constraints

The effective operators we are working with allow for the pair production of WIMPs ($\chi$) in the proton–proton collisions at the LHC. If one of the incoming partons radiates a jet through initial state radiation (ISR), one can observe the process $pp \rightarrow \chi\chi j$ as a single jet associated with missing transverse energy ($E_T^\text{miss}$). In this study, we include the ATLAS [58] monojet analysis based on 139 fb$^{-1}$ of data from Run II. ATLAS has performed a number of further searches for other types of ISR, leading for example to mono-photon signatures, but these are known to give weaker bounds on DM EFTs than monojet searches [74–76].

Starting from UFO files generated using LanHEP v4.0.0 [77], we have then generated the process $pp \rightarrow \chi\chi j$ with MadGraph aMC@NLO v3.4.0 [78] for the ATLAS analysis, interfaced to Pythia v8.3 [79] for parton showering and hadronization. The detector response is simulated using the ATLAS detector configuration [80] in FastJet v3.3.3 [81]. We apply the following kinematic cuts from Ref. [58]: $E_T^\text{miss} > 200$ GeV, a leading jet with $p_T > 150$ GeV and $|\eta| < 2.4$, and up to three additional jets with $p_T > 30$ GeV and $|\eta| < 2.8$.

We validated our analysis by reproducing the green dash-dotted line in figure 5, using a simplified DM model where Dirac fermion WIMPs ($\chi$) are pair-produced from quarks via $s$-channel exchange of a spin-1 mediator particle ($Z_A$) with axial-vector couplings [58].

In this analysis we only include the operators (and combinations of them) that still had mass regions with suitable solutions —OP1, OP3, OP4 and the combinations of OP1&OP2 and OP1&OP3—, allowed even after all the constraints imposed by non-collider experiments that we have considered. The results reported by ATLAS were obtained using proton-proton collision data at a center-of-mass energy of $\sqrt{s} = 13$ TeV. Events were required to have at least one jet with transverse momentum above 200 GeV and no reconstructed leptons or photons. Due to the $\sqrt{s} = 13$ TeV center-of-mass energy, the maximum mass we considered in our simulations was 6.4 TeV. We use the data points in fig. 5 of the measured distributions of $p_T^\text{recoil}$.

Renormalization group effects can produce a sizable running of the Wilson coefficients between the low-energy scales probed in direct detection experiments and the high energies of the LHC (see [82–85] and references therein), which depend on $O_{SM}$, see eq. (1). For our operators in eqs. (2) and (3), QCD effects are negligible. We disregarded QED mixing affecting $A_{\text{eff}}^{L/R}$ (its corresponding operator, OP2, is excluded in the entire region studied).
Figure 5: Measured distributions of $p_T^{\text{recoil}}$ for $p_T^{\text{recoil}} > 200$ GeV selection [58] compared with the SM predictions in the signal region.

5 Discussion and Conclusions

We recall that operators OP2, OP5 and the combinations OP1+OP2, OP2+OP3 and OP4+OP5 were already excluded in the range [50 GeV, 6.4 TeV] by direct detection experiments data. We show below the results obtained by comparing the data from ATLAS [58] (see fig. 5) with the simulated results for each operator. When we combined operators, for every benchmark point evaluated in the simulations, the relation $\Lambda = 2 m_{\text{DM}}$ was used.

| Operator | Dim. | DM candidate | Allowed DM mass (GeV) |
|----------|------|--------------|-----------------------|
| 1. $B_{\mu
u} \bar{\psi} \gamma^{\mu\nu} \Psi$ | 5 | $\Psi$ fermion | $\approx 0.0025 - 2$, $\approx 33 - 44.5$ |
| 2. $(\bar{\psi} \gamma_{\mu} \psi) (\bar{\Psi} \gamma^{\mu} P_{L,R} \Psi)$ | 6 | $\Psi$ fermion | none |
| 3. $B_{\mu
u} \bar{\Psi} (\gamma^{\mu} D_{\nu} - \gamma^{\nu} D_{\mu}) P_{L,R} \Psi$ | 6 | $\Psi$ fermion | $\approx 33 - 44.5$ |
| 4. $B_{\mu
u} X^{\mu\nu} \Phi$ | 5 | vector $X$, scalar $\Phi$ | $\approx 0.11 - 2$, $\approx 36 - 44.5$ |
| 5. $(\bar{\psi} \gamma_{\mu} \psi) \frac{1}{2} \Phi^\dagger \rightarrow D^{\mu} \Phi$ | 6 | scalar $\Phi$ | none |
| $1 \pm 2$ | 5+6 | $\Psi$ fermion | $\approx 0.0025 - 2$ |
| $1 \pm 3$ | 5+6 | $\Psi$ fermion | $\approx 0.0025 - 2$, $\approx 33 - 44.5$ |
| $2 \pm 3$ | 6 | $\Psi$ fermion | none |

Table 1: Summary of results obtained in ref. [1]: considering the $Z$ invisible decay width, relic density, direct detection experiments and indirect detection results from dSphs and positron flux measurements. It is very important to note that we are considering masses of the dark particles below the mass of the $Z$ boson ($M_Z/2 \sim 45.5$ GeV, as they appear in charge conjugated pairs).

We also complemented our previous results from Ref. [1] 6, shown in table 1, so we tested the solutions found according to the experimental data analyzed there, in the region $m_{\text{DM}} < m_Z/2$. We show below the comparison of the simulated events, for masses previously allowed, with the ATLAS data.

5The combinations of OP1&OP2 and OP2&OP3 are ruled out mainly due to the contribution of OP2 to the spin-independent DM-nucleon cross sections, which does not exclude OP1 or OP3 alone. Similarly, the combination of OP4&OP5 is excluded mostly due to the contribution of OP5 to the SI DM-nucleon cross sections, which does not exclude OP4 alone.

6In Ref. [1] we select benchmark values for $\Lambda$ ($230$ GeV $< \Lambda < 1$ TeV), but when we combined operators, its value was irrelevant.
Figure 6: \( p_T \) distributions simulated using OP1 of eq. (4), vs ATLAS data (fig. 5). We use benchmark points for 50 GeV, 100 GeV, 200 GeV and 300 GeV. We see that all these masses are allowed.

Figure 7: \( p_T \) distributions simulated using OP1 of eq. (4), vs ATLAS data (fig. 5). We use benchmark points for (a) 0.0025 GeV, 0.01 GeV, 0.1 GeV and 2 GeV, and (b) 41 GeV, 42 GeV, 43 GeV and 44.5 GeV. We see that masses smaller than 43 GeV are ruled out for this operator.

- **OP1.** In fig. 6 we evaluated \( m_\psi = 50 \) GeV, 100 GeV, 200 GeV and 300 GeV and we observe that all these masses are allowed. In fig. 7 we use the benchmark points (a): 0.0025 GeV, 0.01 GeV, 0.1 GeV and 2 GeV, and (b) 41 GeV, 42 GeV, 43 GeV and 44.5 GeV. We see that masses smaller than 43 GeV are ruled out for this operator.

- **OP3.** We evaluated the masses: 175 GeV, 190 GeV and 225 GeV in fig. 8(a) and 35 GeV, 40 GeV and 44.5 GeV in fig. 8(b). We see in fig. 8(a) that masses larger than 190 GeV are allowed. For this operator the region \( m_\psi < M_Z/2 \) is now entirely excluded.

- **OP4.** In fig. 9 we use the benchmark points: (a) 50 GeV, 100 GeV, 150 GeV, 200 GeV and 300 GeV and (b) 100 GeV, 36 GeV, 40 GeV and 44.5 GeV. We see in both figures that all values are allowed by the data.

- **OP1&OP2.** We use benchmark points for 0.0025 GeV, 0.01 GeV, 0.1 GeV and 2 GeV in fig. 10. We see that all these masses are excluded by the data.

- **OP1&OP3.** We evaluated the masses: (a) 200 GeV, 300 GeV, 325 GeV and 350 GeV, and (b) 50 GeV, 100 GeV, 140 GeV, 150 GeV and 200 GeV. In fig. 11(a) we use the same sign for the effective couplings and in fig. 11(b) we use a relative sign between the operators. The masses allowed are (a) larger than 325
Figure 8: $p_T$ distributions simulated using OP3 of eq. (4), vs ATLAS data (fig. 5). We use benchmark points for (a) 175 GeV, 190 GeV and 225 GeV and (b) 35 GeV, 40 GeV and 44.5 GeV. The plot in (a) shows that masses above 190 GeV are allowed, while in (b) we see that all the region is excluded.

Finally, for DM masses below $M_\zeta/2$, we tested the benchmark points: fig. 12(a) 0.0025 GeV, 0.01 GeV, 0.1 GeV and 2 GeV and fig. 12(b) 35 GeV, 40 GeV, 44 GeV. We see that in both figures the whole mass range is ruled out by the data ($m_{\text{DM}} \in [44 \text{ GeV}, M_\zeta/2]$ was already excluded by analysis of positron measurements, see table 1).

We present a summary of our results in table 2.

| Operator | Dim. | DM candidate | Allowed DM mass |
|----------|------|--------------|-----------------|
| 1.- $B_{\mu\nu}\Psi\sigma^{\mu\nu}\Psi$ | 5 | $\Psi$ fermion | $\gtrsim 43$ GeV * |
| 2.- $(\bar{\psi}\gamma_\mu\psi)(\bar{\Psi}\gamma_\mu P_{L,R}\Psi)$ | 6 | $\Psi$ fermion | none |
| 3.- $B_{\mu\nu}\Psi(\gamma_\mu\bar{D}^\nu - \gamma_\nu\bar{D}^\mu)P_{L,R}\Psi$ | 6 | $\Psi$ fermion | $\gtrsim 190$ GeV |
| 4.- $B_{\mu\nu}\chi^{\mu\nu}\Phi$ | 5 | vector $X$, scalar $\Phi$ | $\gtrsim 30$ GeV * |
| 5.- $(\bar{\psi}\gamma_\mu\psi)\frac{1}{2}\Phi\bar{\Phi}\bar{D}^{\mu}\Phi$ | 5+6 | $\Psi$ fermion | none |
| 1 + 2 | 5+6 | $\Psi$ fermion | none |
| 1 - 3 | 5+6 | $\Psi$ fermion | $\gtrsim 325$ GeV |
| 2 + 3 | 6 | $\Psi$ fermion | $\gtrsim 140$ GeV |

Table 2: Summary of results obtained in this work, which supersede those in our previous paper [1]. In addition to the experimental constraints used therein, now we also considered the limits from ATLAS in ref. [58]. *We note that the region ($M_\zeta \pm \Gamma_\zeta)/2$ is excluded, see Table 1.

The constraining power of ATLAS results forbids mostly light DM particles with masses below $M_\zeta/2$. For OP1 and OP4, we still have solutions below $M_\zeta/2$, while for OP3 and the combination of OP1&OP3 we need larger masses to satisfy the ATLAS constraints. Future LHC analyses will set even tighter constraints on DM, particularly within our EFT and, specifically, for the subset of operators (those with spin-one mediators) considered in this work.

Acknowledgements

We are grateful to José Wudka for valuable discussions and suggestions and to Marco A. Arroyo-Ureña for his helpful guide and advice with the software used in this work. F. F. acknowledges financial support from CONACyT graduate grants program No. 728500. P. R is indebted to Cátedras Marcos Moshinsky (Fundación Marcos Moshinsky) and CONACyT (‘Paradigmas y Controversias de la Ciencia 2022’, Project No. 319395).
Figure 9: $p_T$ distributions simulated using OP4 of eq. (4), vs ATLAS data (fig. 5). We use benchmark points for (a) 50 GeV, 100 GeV, 150 GeV, 200 GeV and 300 GeV and (b) 36 GeV, 40 GeV and 44.5 GeV. We see that all these masses are allowed.

Figure 10: $p_T$ distributions simulated using OP1&OP2 of eq. (4), vs ATLAS data (fig. 5). We use benchmark points for 0.0025 GeV, 0.01 GeV, 0.1 GeV and 2 GeV. We see that all these masses are ruled out.

References

[1] Fabiola Fortuna, Pablo Roig, and José Wudka. Effective field theory analysis of dark matter-standard model interactions with spin one mediators. *JHEP*, 02:223, 2021.

[2] Arcadi, Giorgio, Dutra, Maíra, Ghosh, Pradipta, Lindner, Manfred, Mambrini, Yann, Pierre, Mathias, Profumo, Stefano, and Queiroz, Farinaldo S. The waning of the wimp? a review of models, searches, and constraints. *Eur. Phys. J. C*, 78(3):203, 2018.

[3] Leszek Roszkowski, Enrico Maria Sessolo, and Sebastian Trojanowski. WIMP dark matter candidates and searches—current status and future prospects. *Rept. Prog. Phys.*, 81(6):066201, 2018.

[4] Marc Schumann. Direct Detection of WIMP Dark Matter: Concepts and Status. *J. Phys. G*, 46(10):103003, 2019.

[5] Changbo Fu et al. Spin-Dependent Weakly-Interacting-Massive-Particle–Nucleon Cross Section Limits from First Data of PandaX-II Experiment. *Phys. Rev. Lett.*, 118(7):071301, 2017. [Erratum: Phys. Rev. Lett.120,no.4:049902(2018)].
Figure 11: $p_T$ distributions simulated using (a) OP1+OP3 and (b) OP1-OP3 of eq. (4), vs ATLAS data (fig. 5). We use benchmark points for (a) 200 GeV, 300 GeV, 325 GeV and 350 GeV and (b) 50 GeV, 100 GeV, 140 GeV, 150 GeV and 200 GeV. The masses allowed are (a) above 325 GeV and (b) above 140 GeV.

[6] E. Aprile et al. First Dark Matter Search Results from the XENON1T Experiment. Phys. Rev. Lett., 119(18):181301, 2017.
[7] D. S. Akerib et al. Results on the Spin-Dependent Scattering of Weakly Interacting Massive Particles on Nucleons from the Run 3 Data of the LUX Experiment. Phys. Rev. Lett., 116(16):161302, 2016.
[8] E. Behnke et al. Final Results of the PICASSO Dark Matter Search Experiment. Astropart. Phys., 90:85–92, 2017.
[9] D. S. Akerib et al. Results from a search for dark matter in the complete LUX exposure. Phys. Rev. Lett., 118(2):021303, 2017.
[10] Andi Tan et al. Dark Matter Results from First 98.7 Days of Data from the PandaX-II Experiment. Phys. Rev. Lett., 117(12):121303, 2016.
[11] Shaul Hanany et al. PICO: Probe of Inflation and Cosmic Origins. 2019.
[12] Dan Hooper and Lisa Goodenough. Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope. Phys. Lett., B697:412–428, 2011.
[13] Esra Bulbul, Maxim Markevitch, Adam Foster, Randall K. Smith, Michael Loewenstein, and Scott W. Randall. Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. Astrophys. J., 789:13, 2014.
[14] O. Urban, N. Werner, S. W. Allen, A. Simionescu, J. S. Kaastra, and L. E. Strigari. A Suzaku Search for Dark Matter Emission Lines in the X-ray Brightest Galaxy Clusters. Mon. Not. Roy. Astron. Soc., 451(3):2447–2461, 2015.
[15] K. Choi et al. Search for neutrinos from annihilation of captured low-mass dark matter particles in the Sun by Super-Kamiokande. Phys. Rev. Lett., 114(14):141301, 2015.
[16] Oleg Ruchayskiy, Alexey Boyarsky, Dmytro Iakubovskyi, Esra Bulbul, Dominique Eckert, Jeroen Franse, Denys Malyshev, Maxim Markevitch, and Andrii Neronov. Searching for decaying dark matter in deep XMM–Newton observation of the Draco dwarf spheroidal. Mon. Not. Roy. Astron. Soc., 460(2):1390–1398, 2016.
[17] M. Ackermann et al. Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data. Phys. Rev. Lett., 115(23):231301, 2015.
Figure 12: $p_T$ distributions simulated using OP1 & OP3 of eq. (4), vs ATLAS data (fig. 5). We use benchmark points for (a) 0.0025 GeV, 0.01 GeV, 0.1 GeV and 2 GeV and (b) 35 GeV, 40 GeV and 44 GeV. In (a) all the masses are ruled out by the data, while in (b) masses larger than 44 GeV are allowed.

[18] Jeroen Franse et al. Radial Profile of the 3.55 keV line out to $R_{200}$ in the Perseus Cluster. *Astrophys. J.*, 829(2):124, 2016.

[19] F. A. Aharonian et al. Hitomi constraints on the 3.5 keV line in the Perseus galaxy cluster. *Astrophys. J.*, 837(1):1, 2017.

[20] Ming-Yang Cui, Qiang Yuan, Yue-Lin Sming Tsai, and Yi-Zhong Fan. Possible dark matter annihilation signal in the AMS-02 antiproton data. *Phys. Rev. Lett.*, 118(19):191101, 2017.

[21] M. G. Aartsen et al. Search for annihilating dark matter in the Sun with 3 years of IceCube data. *Eur. Phys. J.*, C77(3):146, 2017. [Erratum: *Eur. Phys. J.C79*, no.3, 214(2019)].

[22] M. Ackermann et al. The Fermi Galactic Center GeV Excess and Implications for Dark Matter. *Astrophys. J.*, 840(1):43, 2017.

[23] N. Aghanim et al. Planck 2018 results. VI. Cosmological parameters. *Astron. Astrophys.*, 641:A6, 2020. [Erratum: *Astron. Astrophys.* 652, C4 (2021)].

[24] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov. Dark matter direct detection rate in a generic model with micrOMEGAs 2.2. *Comput. Phys. Commun.*, 180:747–767, 2009.

[25] Jessica Goodman, Masahiro Ibe, Arvind Rajaraman, William Shepherd, Tim M. P. Tait, and Hai-Bo Yu. Constraints on Dark Matter from Colliders. *Phys. Rev.*, D82:116010, 2010.

[26] Andreas Crivellin and Ulrich Haisch. Dark matter direct detection constraints from gauge bosons loops. *Phys. Rev.*, D90:115011, 2014.

[27] Andreas Crivellin, Francesco D’Eramo, and Massimiliano Procura. New Constraints on Dark Matter Effective Theories from Standard Model Loops. *Phys. Rev. Lett.*, 112:191304, 2014.

[28] Mateusz Duch, Bohdan Grzadkowski, and Jose Wudka. Classification of effective operators for interactions between the Standard Model and dark matter. *JHEP*, 05:116, 2015.

[29] Subhaditya Bhattacharya and Jose Wudka. Effective theories with dark matter applications. *Int. J. Mod. Phys. D*, 30(13):2130004, 2021.

[30] Basabendu Barman, Subhaditya Bhattacharya, Sudhakantha Girmohanta, and Sahabub Jahedi. Effective Leptophilic WIMPs at the $e^+e^-$ collider. *JHEP*, 04:146, 2022.
[31] Giorgio Arcadi, Abdelhak Djouadi, and Martti Raidal. Dark Matter through the Higgs portal. 2019.

[32] Nicolas Cosme, Laura Lopez Honorez, and Michel H. G. Tytgat. Leptogenesis and dark matter related? \textit{Phys. Rev.}, D72:043505, 2005.

[33] Haipeng An, Shao-Long Chen, Rabindra N. Mohapatra, and Yue Zhang. Leptogenesis as a Common Origin for Matter and Dark Matter. \textit{JHEP}, 03:124, 2010.

[34] Adam Falkowski, Jose Juknevich, and Jessie Shelton. Dark Matter Through the Neutrino Portal. 2009.

[35] Manfred Lindner, Alexander Merle, and Viviana Niro. Enhancing Dark Matter Annihilation into Neutrinos. \textit{Phys. Rev.}, D82:123529, 2010.

[36] Yasaman Farzan. Flavoring Monochromatic Neutrino Flux from Dark Matter Annihilation. \textit{JHEP}, 02:091, 2012.

[37] Adam Falkowski, Joshua T. Ruderman, and Tomer Volansky. Asymmetric Dark Matter from Leptogenesis. \textit{JHEP}, 05:106, 2011.

[38] Julian Heeck and He Zhang. Exotic Charges, Multicomponent Dark Matter and Light Sterile Neutrinos. \textit{JHEP}, 05:164, 2013.

[39] Seungwon Baek, P. Ko, and Wan-Il Park. Singlet Portal Extensions of the Standard Seesaw Models to a Dark Sector with Local Dark Symmetry. \textit{JHEP}, 07:013, 2013.

[40] Iason Balbes, Nicole F. Bell, Alexander J. Millar, and Raymond R. Volkas. Asymmetric Dark Matter and CP Violating Scatterings in a UV Complete Model. \textit{JCAP}, 1510:048, 2015.

[41] Vannia Gonzalez-Macias, Jose I. Illana, and Jose Wudka. A realistic model for Dark Matter interactions in the neutrino portal paradigm. \textit{JHEP}, 05:171, 2016.

[42] Brian Batell, Tao Han, and Barmak Shams Es Haghi. Indirect Detection of Neutrino Portal Dark Matter. \textit{Phys. Rev.}, D97(9):095020, 2018.

[43] S. HajiSadeghi, S. Smolenski, and J. Wudka. Asymmetric dark matter with a possible Bose-Einstein condensate. \textit{Phys. Rev.}, D99(2):023514, 2019.

[44] Priyotosh Bandyopadhyay, Eung Jin Chun, Rusa Mandal, and Farinaldo S. Queiroz. Scrutinizing Right-Handed Neutrino Portal Dark Matter With Yukawa Effect. \textit{Phys. Lett.}, B788:530–534, 2019.

[45] Asher Berlin and Nikita Blinov. Thermal neutrino portal to sub-MeV dark matter. \textit{Phys. Rev.}, D99(9):095030, 2019.

[46] M. Blennow, E. Fernandez-Martinez, A. Olivares-Del Campo, S. Pascoli, S. Rosauro-Alcaraz, and A. V. Titov. Neutrino Portals to Dark Matter. \textit{Eur. Phys. J.}, C79(7):555, 2019.

[47] Eleanor Hall, Thomas Konstandin, Robert McGehee, and Hitoshi Murayama. Asymmetric Matters from a Dark First-Order Phase Transition. 11 2019.

[48] Eleanor Hall, Thomas Konstandin, Robert McGehee, Hitoshi Murayama, and Géraldine Servant. Baryogenesis From a Dark First-Order Phase Transition. \textit{JHEP}, 04:042, 2020.

[49] Vannia Gonzalez Macias and Jose Wudka. Effective theories for Dark Matter interactions and the neutrino portal paradigm. \textit{JHEP}, 07:161, 2015.

[50] R. L. Workman and Others. Review of Particle Physics. \textit{PTEP}, 2022:083C01, 2022.

[51] E. Aprile et al. Dark Matter Search Results from a One Ton-Year Exposure of XENON1T. \textit{Phys. Rev. Lett.}, 121(11):111302, 2018.

[52] Xiangxiang Ren et al. Constraining Dark Matter Models with a Light Mediator at the PandaX-II Experiment. \textit{Phys. Rev. Lett.}, 121(2):021304, 2018.
A. J. Brennan, M. F. McDonald, J. Gramling, and T. D. Jacques. Collide and Conquer: Constraints on Simplified Dark Matter Models using Mono-X Collider Searches. *JHEP*, 05:112, 2016.

Martin Bauer, Martin Klassen, and Valentin Tenorth. Universal properties of pseudoscalar mediators in dark matter extensions of 2HDMs. *JHEP*, 07:107, 2018.

A. Semenov. LanHEP — A package for automatic generation of Feynman rules from the Lagrangian. Version 3.2. *Comput. Phys. Commun.*, 201:167–170, 2016.

J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *JHEP*, 07:079, 2014.

Christian Bierlich et al. A comprehensive guide to the physics and usage of PYTHIA 8.3. 3 2022.

Jack Y. Araz, Benjamin Fuks, and Georgios Polykratis. Simplified fast detector simulation in MADANALYSIS 5. *Eur. Phys. J. C*, 81(4):329, 2021.

Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. FastJet User Manual. *Eur. Phys. J. C*, 72:1896, 2012.

Fady Bishara, Joachim Brod, Benjamin Grinstein, and Jure Zupan. Chiral Effective Theory of Dark Matter Direct Detection. *JCAP*, 02:009, 2017.

Fady Bishara, Joachim Brod, Benjamin Grinstein, and Jure Zupan. DirectDM: a tool for dark matter direct detection. 8 2017.

Fady Bishara, Joachim Brod, Benjamin Grinstein, and Jure Zupan. From quarks to nucleons in dark matter direct detection. *JHEP*, 11:059, 2017.

Fady Bishara, Joachim Brod, Benjamin Grinstein, and Jure Zupan. Renormalization Group Effects in Dark Matter Interactions. *JHEP*, 03:089, 2020.