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Spin-0[±] portal induced Dark Matter

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ABSTRACT: Standard model (SM) spin-zero singlets are constrained through their di-Bosonic decay channels *via* an effective coupling induced by a vector-like quark (VLQ) loop at the LHC for $\sqrt{s} = 13$ TeV. These spin-zero resonances are then considered as portals for scalar, vector or fermionic dark matter particle interactions with SM gauge bosons. We find that the model is validated with respect to the observations from LHC data and from cosmology, indirect and direct detection experiments for an appreciable range of scalar, vector and fermionic DM masses greater than 300 GeV and VLQ masses ≥ 400 GeV, corresponding to the three choice of portal masses 270 GeV, 500 GeV and 750 GeV respectively.

KEYWORDS: Beyond Standard Model, Cosmology of Theories beyond the SM

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1 Introduction

ATLAS and CMS [1–4] have been assiduously searching for di-Boson production in the semileptonic, fully leptonic and di-Bosonic channels at $\sqrt{s} = 13$ TeV with the integrated luminosity of 3.2 fb^{-1} . They have looked for a scalar spin zero resonance of mass > 200 GeV and a spin 2 Randall-Sundrum graviton state as benchmark model of mass > 500 GeV. Assuming a scaling of cross-section for an s-channel resonance produced by gluon fusion (light quark-antiquark annihilations) the consistency between the 13 TeV data and the data collected at the 8 TeV is found at the level of 1.2 (2.1) standard deviation. An excess of di-photon events at a mass of 750 GeV reported by the LHC’s ATLAS and CMS experiments in 2015 had led to a flurry of activity resulting in more than 500 papers in a short span of time (see for example [5] and references therein). The LHC phenomenology of the 750 GeV di-photon resonance was also studied in the framework of the effective field theory (EFT) and extended to include this new found resonance induced interactions of the standard model (SM) singlet fermionic and/ or scalar DM with the SM gauge Bosons of the visible world [6–10]. The excess reported in 2015 however did not show up in 2016 data. ATLAS and CMS results of run 1 at LHC also saw the enhanced production of SM Higgs Boson in association with a top quark. A possible explanation put forward in [11] was to interpret

the data due to the existence of another heavier scalar with the best fit mass of 272_{-9}^{+12} GeV. This particle unlike the SM Higgs was supposed to interact with dark matter. The most promising mechanism for the production of di-photon resonance discussed in the literature is through gluon-gluon fusion and its subsequent decay into SM di-Bosons *viz* $gg \rightarrow \phi^0/A^0 \rightarrow \gamma\gamma$. We will examine the possibility of this resonance to act as a portal between the dark matter particle (DM) of any spin (0, 1/2, 1) with the SM particles and examine the constraints on the model parameters from the observed relic density, direct and indirect observations while satisfying the constraints from ATLAS and CMS results [1–4].

In section 2 we describe a simple renormalizable model by augmenting the particle content of the SM to include an $SU(2)_L$ singlet scalar/pseudo-scalar particle and vector-like SM colour-triplet fermions of exotic charge Q_ψ . The DM particles in this model are neutral SM $SU(2)_L \times U(1)_Y$ singlets which are odd under a discrete Z_2 symmetry and can be scalars, fermions or vectors. These particles interact with the SM gauge Bosons through the scalar/pseudo-scalar portal. We compute the partial decay-widths of the scalar and pseudo-scalar in the subsection 2.1. In the subsection 2.2 we analyse the di-Boson production cross-section observed by the ATLAS and the CMS experiments [1] in $p-p$ collision in the context of the model discussed here and obtain constraints on the coupling of the di-Boson resonance with vector-like fermions. With these constrained couplings of the portal scalar and pseudo-scalar, we compute the relic density contribution of the viable DM candidates through their interactions with the visible world in the subsection 3.1. The indirect detection of the DM candidates through the emission of monochromatic γ -rays by Fermi-LAT [12, 13], a satellite based γ ray observatory and the ground based Cherenkov telescope H.E.S.S. [14, 15] is discussed in the subsection 3.2. Further, we investigate the possibility of direct detection of such DM particles in the elastic DM-nucleon scattering experiments in Dark-Side50 (2016) [16], LUX [17, 18], XENON [19, 20] and PANDA [21] collaborations in the subsection 3.3. Section 4 summaries our analysis and results through composite figures, where all experimental constraints are used to look out for allowed region of the model.

2 The model

We consider a portal induced dark matter model in which the di-Boson resonance is either a CP even scalar (Φ) or a CP odd (P) scalar. The di-Boson coupling is introduced through vector-like $SU(3)_C$ triplet fermion with exotic charge $Q_\psi = +5/3$. In addition we propose the dark matter to be a real scalar, a real vector or a spin 1/2 Dirac fermion. In order to avoid mixing of the VLQ's with SM quarks and to stabilise the DM particles we invoke an Abelian $U(1)_d$ gauge symmetry. The $U(1)_d$ sector gauge Lagrangian contains

$$\mathcal{L}_d \subset -\frac{1}{4}V_{\mu\nu}^0 V^{0\mu\nu} + (\mathcal{D}_\mu\varphi)^\dagger (\mathcal{D}^\mu\varphi) - V(\varphi) \quad (2.1)$$

where φ is a charged scalar, $V_{\mu\nu}^0$ is the $U(1)_d$ field strength tensor of the gauge field V_μ^0 and $V(\varphi)$ is the scalar potential. The charged scalar field in the dark sector allows the spontaneous breaking of $U(1)_d$ gauge symmetry to a Z_2 subgroup after φ develops a non-zero VEV v_φ . The imaginary part of φ is eaten up by V_μ^0 to give it a mass $m_{V^0} = \lambda_\varphi v_\varphi/2$,

where λ_φ is the gauge coupling [22, 23]. The usual charge conjugation Z_2 symmetry $V_\mu^0 \rightarrow -V_\mu^0$ makes this massive gauge field a viable stable DM candidate.

The Lagrangian of the model is given as follows:

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_\psi^{\text{VLQ}} - V(H, \Phi, P) + \mathcal{L}_{\mathcal{DM}} \quad (2.2)$$

where

$$\begin{aligned} V(H, \Phi, P) = & \mu^2 |H|^2 + \lambda |H|^4 + \mu_\Phi^2 |\Phi|^2 + \mu_P^2 |P|^2 + \lambda_\Phi |\Phi|^4 + \lambda_P |P|^4 \\ & + \lambda_{H\Phi} |H|^2 |\Phi|^2 + \lambda_{HP} |H|^2 |P|^2 + \lambda_{\Phi P} |P|^2 |\Phi|^2. \end{aligned} \quad (2.3)$$

Here H is the SM Higgs $SU(2)_L$ doublet and $\mu^2, \mu_\Phi^2 < 0$ and $\mu_P^2 > 0$. After spontaneous symmetry breaking, CP even scalar Φ picks up a VEV and can be written as $\Phi = v_\Phi + \phi^0$, where $\langle \Phi \rangle \equiv v_\Phi = \sqrt{\frac{-\mu_\Phi^2}{2\lambda_\Phi}}$ and $P \equiv iA^0$.

The Lagrangian after the electroweak and $U(1)_d$ symmetry breaking is re-written as

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}^{\text{VLQ}} + \mathcal{L}^{\text{portal}} + \mathcal{L}_{\mathcal{DM}}^{\text{scalar}} + \mathcal{L}_{\mathcal{DM}}^{\text{vector}} + \mathcal{L}_{\mathcal{DM}}^{\text{fermion}} \quad (2.4)$$

where

$$\mathcal{L}_\psi^{\text{VLQ}} = \bar{\psi} (i \gamma^\mu \not{D}_\mu - m_\psi) \psi + y_{\phi^0} \bar{\psi} \psi \phi^0 + y_{A^0} \bar{\psi} \gamma_5 \psi A^0 \quad (2.5)$$

$$\mathcal{L}_{\text{portal}} = \frac{1}{2} |\partial_\mu \phi^0|^2 - \frac{1}{2} m_{\phi^0}^2 \phi^{02} + \frac{1}{2} |\partial_\mu A^0|^2 - \frac{1}{2} m_{A^0}^2 A^{02} \quad (2.6)$$

$$\mathcal{L}_{\mathcal{DM}}^{\text{scalar}} = \frac{1}{2} |\partial_\mu \eta|^2 - \frac{1}{2} m_\eta^2 \eta^2 + \frac{1}{2} v_\Phi \kappa_{\eta\phi^0} \eta^2 \phi^0 \quad (2.7)$$

$$\mathcal{L}_{\mathcal{DM}}^{\text{vector}} = -\frac{1}{4} V_{\mu\nu}^0 V^{0\mu\nu} - \frac{1}{2} m_{V^0}^2 V^{0\mu} V^0_\mu + \frac{1}{2} v_\Phi \kappa_{V^0\phi^0} V^0_\mu V^{0\mu} \phi^0 \quad (2.8)$$

$$\mathcal{L}_{\mathcal{DM}}^{\text{fermion}} = \bar{\chi} (i \gamma^\mu \partial_\mu - m_\chi) \chi + \kappa_{\chi\phi^0} \bar{\chi} \chi \phi^0 + i \kappa_{\chi A^0} \bar{\chi} \gamma_5 \chi A^0 \quad (2.9)$$

where $D_\mu = \partial_\mu - g_s \lambda^a G_\mu^a - g' y_f B_\mu$, $m_{A^0}^2 = \mu_P^2$ and $m_{\phi^0}^2 = -4 \mu_\Phi^2$. The quantum number assignments of new scalars, pseudo-scalar, vector-Boson and fermions of the dark $U(1)_d$ sector under the gauge symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_d$ is given in table 1.

In general Φ and P will mix with SM Higgs and consequently the DM scalar η will interact with SM particles through the Higgs portal unless $\lambda_{H\Phi}$ (λ_{HP}) is zero. Even in the absence of $\lambda_{H\Phi}$ (λ_{HP}) term, a mixing term $h^0 - \phi^0$ ($h^0 - A^0$) will be generated radiatively through multi-loop diagrams as shown in figure 1 and will be highly suppressed. Recently, the authors of reference [24] have reviewed the scalar induced DM models and considered such $\sim 10\%$ Higgs mixing with the scalar portal, to generate the required DM relic density in the universe. However, we will assume this term is absent and the radiatively induced portal ϕ^0/A^0 - Higgs mixing is negligible such that the DM interacts with SM particles albeit gauge-boson pairs only through the di-Boson portal.

The decay of $(3, 1, 5/3)$ VLQ is protected by Z_2 symmetry and the lifetime of such singlet VLQs is naturally large, as there is no renormalizable, gauge invariant operator to mediate their decays into SM particles. However, VLQs form a bound state which can

Figure 1. Radiatively generated $h^0 - \phi^0$ ($h^0 - A^0$) mixing diagram induced by the VLQ and top quark at the highly suppressed three loop level.

Particle	Spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_d$	Z_2
Di-Boson portal						
ϕ^0	0	1	1	0	0	+
A^0	0	1	1	0	0	+
Vector Like quark ψ	$\frac{1}{2}$	3	1	$\frac{5}{3}$	a	—
Dark Matter particle						
η	0	1	1	0	0	—
χ	$\frac{1}{2}$	1	1	0	b	—
V^0	1	1	1	0	0	—

Table 1. Quantum number assignments of new scalars, pseudo-scalar, vector-Boson and fermions of the dark $U(1)_d$ sector under the gauge symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_d$.

decay through non-trivial mechanism. This subject has been analysed in detail by the authors of reference [25], where they have also considered the possibility of introducing an additional Z_2 odd VLQ doublet ψ' in the $(3, 2, 7/6)$ representation facilitating the decay of the singlet VLQ *via* an off-shell ψ' with the constraint $m_{\psi'} > m_{\psi}$ such that the extra VLQ does not contribute appreciably to the di-photon spectrum. On the other hand, the authors of reference [26] while exploring the various co-annihilation scenarios where the colored VLQ's are slightly heavier than some new dark matter state so that they lie in the compressed spectra also found that VLQ's are likely to hadronize before they can decay. This bound state formation of VLQ opens up the frontier to look for the new resonances at the ongoing and proposed particle accelerators. In LHC, one can expect to observe the second peak at $\sim 2m_{\psi}$ in the di-Boson invariant mass distribution in $pp \rightarrow \gamma\gamma, \gamma Z$, and ZZ channels, following the primary peak due to the scalar/ pseudo-scalar portal at m_{ϕ^0/A^0} and the preliminary theoretical exercise has been performed in reference [25].

2.1 Partial decay-widths to gauge Bosons

Interactions described in equations (2.5)–(2.9) indicate that there are no tree level couplings of the singlet scalar and pseudo-scalar with the SM neutral gauge Bosons. However, the non-vanishing couplings are generated at the level of one loop which are induced by fermions. The dominant one loop contribution comes from the VLQ which is the heaviest fermion available in our model. They are evaluated in the appendix A. These one loop amplitudes can then be translated in the language of the effective field theory as the effective

Figure 2. Figure 2a, depicts the variation of the partial decay-widths of the scalar with the VLQ mass m_ψ for the three values of the decaying scalar masses 270, 500, 750 GeV respectively and figure 2b shows the partial decay-widths of the 270 GeV scalar to pair of gg , $\gamma\gamma$, γZ and ZZ gauge Bosons respectively.

Figure 3. Figure 3a, depicts the variation of the partial decay-widths of the pseudo-scalar with the VLQ mass m_ψ for the three values of the decaying pseudo-scalar masses 270, 500, 750 GeV respectively and figure 3b shows the partial decay-widths of the 270 GeV pseudo-scalar to pair of gg , $\gamma\gamma$, γZ and ZZ gauge Bosons respectively.

couplings of the three interacting fields. They become the coefficients of the four distinct effective interacting three point vertices, each for scalar and pseudo-scalar. The resulting effective Lagrangians can then be written as

$$\mathcal{L}_{\text{eff}}^{\phi^0} = \kappa_{gg} \phi^0 G_{\mu\nu}^a G_a^{\mu\nu} + \kappa_{\gamma\gamma} \phi^0 F_{\mu\nu} F^{\mu\nu} + \kappa_{Z\gamma} \phi^0 F_{\mu\nu} Z^{\mu\nu} + \kappa_{ZZ} \phi^0 Z_{\mu\nu} Z^{\mu\nu} \quad (2.10a)$$

$$\mathcal{L}_{\text{eff}}^{A^0} = \tilde{\kappa}_{gg} A^0 G_{\mu\nu}^a \tilde{G}_a^{\mu\nu} + \tilde{\kappa}_{\gamma\gamma} A^0 F_{\mu\nu} \tilde{F}^{\mu\nu} + \tilde{\kappa}_{Z\gamma} A^0 F_{\mu\nu} \tilde{Z}^{\mu\nu} + \tilde{\kappa}_{ZZ} A^0 Z_{\mu\nu} \tilde{Z}^{\mu\nu} \quad (2.10b)$$

Using the effective Lagrangians (2.10a) and (2.10b) the partial decay-widths of a CP even and odd scalars are calculated in terms of the loop integrals in appendix A. We studied the variation of the partial decay-widths $\Gamma_{\phi^0 \rightarrow \gamma\gamma}$ with the VLQ mass m_ψ varying between 400 GeV–1.6 TeV for the three choice of the scalar portal masses namely $m_{\phi^0} = 270, 500$

Figure 4. Three band of contours showing the 2σ limits on the coupling in the $m_\psi - y_{\phi^0/A^0}$ plane, w.r.t. the central value of the di-photon production cross-section as observed at $\sqrt{s} = 13$ TeV from the CMS and ATLAS collaborations in Run 2 [1–3] corresponding to the three scalar/ pseudo-scalar masses 270, 500 and 750 GeV respectively. The left and right panels are for the scalar and pseudo-scalar panels respectively.

and 750 GeV in figure 2a. We also compare the partial decaywidth of the scalar to the di-photon channel with the dominant channel $\phi^0 \rightarrow gg$ and the suppressed channels of $\phi^0 \rightarrow \gamma Z$ and $\phi^0 \rightarrow ZZ$ in figure 2b.

Similarly the pseudo-scalar partial decay-width variations are shown in figures 3a and 3b.

2.2 Constraints on the model from LHC

We study the production cross-section of these exotic scalar and/ or pseudo-scalar at the LHC ($pp \rightarrow \phi^0/A^0 \rightarrow V_1 V_2$). The di-photon production cross-section $\sigma(pp \rightarrow \phi^0/A^0 \rightarrow \gamma\gamma)$ is mainly through gluon fusion. As shown in the previous section that the partial decay-widths of scalar / pseudo-scalar being negligibly small in comparison to their masses, we can calculate the production of SM di-Bosons V_1 and V_2 ($V_{1,2} \equiv \gamma, Z$) in the narrow width approximation of the scalar (or pseudo-scalar). The cross-section is given as

$$\sigma_{V_1 V_2} = \frac{\pi^2}{8m_{\phi^0/A^0}} \Gamma(\phi^0/A^0 \rightarrow gg) \frac{1}{s} \text{BR}(\phi^0/A^0 \rightarrow V_1 V_2) \int \frac{dx}{x} g(x) g\left(\frac{m_{\phi^0/A^0}^2}{sx}\right). \quad (2.11)$$

Using equation (2.11), we evaluate the cross-sections for the processes $pp \rightarrow \gamma\gamma, gg, \gamma Z, ZZ$ and compare with the observations for a spin $0^\pm$ resonance mass in the narrow width approximation from the CMS and ATLAS run II collaboration at $\sqrt{s} = 13$ TeV and an integrated luminosity of 3.2 fb^{-1} [1–3]. We have tabulated these results only for the $\gamma\gamma$ and γZ channels for the benchmark resonance masses $m_{\phi^0}/m_{A^0} = 270 \text{ GeV}, 500 \text{ GeV}$ and 750 GeV in table 2.

Figures 4a and 4b show the 2-sigma limits on the couplings allowed by the LHC data at $\sqrt{s} = 13$ TeV (as given in table 2) in the plane defined by the VLQ mass m_ψ and its coupling with the y_{ϕ^0}/y_{A^0} for the scalar and pseudo-scalar portal respectively. Each plot

Figure 5. In the left panel we depict relic density contours satisfying $\Omega_c h^2 = 0.1138 \pm .0045$ in the plane defined by scalar (vector) DM mass m_η (m_{V^0}) and scalar (vector) DM-mediator coupling $\kappa_{\eta\phi^0}$ ($\kappa_{V^0\phi^0}$) for a fixed scalar mediator mass of 270 GeV corresponding to the four choice of VLQ masses 400, 800, 1200 and 1600 GeV respectively. In the right panel we have exhibited the constant relic density contours for a fixed VLQ mass of 400 GeV corresponding to the three different choices of the portal scalar mass 270, 500 and 750 GeV respectively. Shaded regions appearing in blue, golden yellow and red correspond to the relic density allowed regions for the portal mass of 270, 500 and 750 GeV respectively.

Figure 6. In figure 6a we depict the relic density contours satisfying $\Omega_c h^2 = 0.1138 \pm .0045$ in the plane defined by fermionic DM mass m_χ and scalar DM mediator coupling $\kappa_{\chi\phi^0}$ for a fixed scalar mediator mass of 270 GeV corresponding to the four choice of VLQ masses 400, 800, 1200 and 1600 GeV respectively. In figure 6b we have exhibited the constant relic density contours for a fixed VLQ mass of 400 GeV corresponding to the three different choices of the portal scalar mass 270, 500 and 750 GeV respectively. Similarly, in figures 6c and 6d the constant relic density contours are drawn for the fixed pseudo-scalar mass of 270 GeV corresponding to four VLQ masses and for the fixed VLQ mass of 400 GeV corresponding to the three pseudo-scalar masses respectively. Shaded regions appearing in blue, golden yellow and red correspond to the relic density allowed regions for the portal mass of 270, 500 and 750 GeV respectively.

m_{ϕ^0}/m_{A^0}	$\sigma_{pp \rightarrow \gamma\gamma}$ (fb)	$\sigma_{pp \rightarrow \gamma Z}$ (fb)
270 GeV	12.70	32.49
500 GeV	3.96	10.58
750 GeV	2.13	6.41

Table 2. Upper limits on the cross-section for spin $0^\pm$ resonances in the narrow width approximation from run II ATLAS collaboration at $\sqrt{s} = 13$ TeV and an integrated luminosity of 3.2 fb^{-1} [1–3].

depicts the three different bands of allowed region corresponding to the three choices of scalar or pseudo-scalar masses 270, 500 and 750 GeV respectively.

3 Portal induced dark matter scenarios

DM which are popularly known as weakly interacting massive particle (WIMP) do not have either electromagnetic or strong interactions. One of the most challenging tasks today is to identify the nature of the DM particle [27].

Since the investigation of the nature of the DM particles needs an understanding of the underlying physics of the model and vice-versa, we would like to begin our analysis by considering the spin of DM particle to be either 0, 1 and/ or 1/2. Before, proceeding with the analysis, we consider the existing cosmological constraints on such a DM candidate from the WMAP [28, 29] and Planck data [30].

3.1 DM pair-annihilation and relic density

In the model described above in section 2, the proposed scalar η , vector V^0 and fermion χ DM candidates can interact with the SM gauge-bosons through CP even ϕ^0 and odd A^0 scalars respectively. In the early universe SM particles remained in thermal equilibrium as long as their reaction rate was faster than expansion rate of the universe. As the universe cooled, the reaction rate fell below the expansion rate and DM particles de-coupled from the thermal bath and contributed to the relic density observed today. The equilibrium in the early universe was maintained via the leading DM pair annihilation processes *viz* into pair of SM particles. The vector-like quark-antiquark pair and a pair of portal scalar/pseudo-scalar can also be produced as a result of the annihilation of DM particles provided mass of the DM particle is higher than those of ψ and/ or ϕ^0/A^0 .

Therefore as a next logical step we compute the thermal averaged DM pair-annihilation cross section. The DM pair annihilation is facilitated through the portal mediated s channel processes assuming the momentum transfer in the scattering to be much less than the portal mass. These annihilation processes lead to the following visible final states: gg , $\gamma\gamma$, γZ and ZZ . Therefore, the s channel processes at such low energy appears to be an effective point interaction among the SM vector bosons and pair of DM candidates, suppressed by the portal mass squared. As to the couplings of Dark Matter with the portal, we consider two different cases, namely

- (a) Scalar portal couplings to the scalar, vector and Fermion DM pair which are defined by $\kappa_\eta\phi^0$, $\kappa_{V^0\phi^0}$, $\kappa_\chi\phi^0$ respectively.
- (b) Pseudo-scalar portal couplings to the fermions which is defined as $\kappa_\chi A^0$.

In the appendix B.1, we calculate the thermal averaged cross-section for the scalar DM pair annihilation *via* scalar portal to the above visible states and are given in equations (B.1)–(B.4). In addition, to these the pair annihilation also lead to a production of the vector like quark- antiquark pair *via* the scalar portal and its thermal averaged cross-section is given in equation (B.5), which is kinematically possible, only for DM mass greater than VLQ mass.

The corresponding thermal averaged cross-section for the annihilation of vector DM to SM gauge Bosons can be obtained directly by substituting $\kappa_{\eta\phi^0}$ by $\kappa_{V^0\phi^0}/3$, v_Φ by v_Φ and m_η by m_{V^0} in equations (B.1)–(B.4). For the VLQ pair production we multiply a factor 1/6 to the contribution given by scalar DM in (B.5).

The thermalized fermionic DM pair annihilation cross-section for the corresponding final states are given in equations (B.7)–(B.11). These cross-sections for every annihilation channel are p -wave suppressed unlike the scalar DM case and thus result in low thermally averaged cross-sections. Therefore, the sensitivity of the fermionic DM-scalar mediator coupling is an order of magnitude less sensitive than those of the corresponding couplings of the scalar and vector DM candidates with the portal.

In addition, the t -channel annihilation diagrams also contribute to the relic density, where DM pair annihilation to a pair of portal scalars can become kinematically feasible for DM mass $\geq m_{\phi^0}$. The thermal averaged cross-sections for these processes are given in equations (B.6) and (B.12) for pair annihilation of scalar and fermionic DM respectively. The contribution of the vector DM pair annihilation to the pair production of such scalars *via* t channel is found to be identical to that of the scalar as given in (B.6).

Unlike the scalar portal case, pseudo-scalar cannot decay to two scalar or vector DM pairs and leaving no choice but to consider relevant spin 1/2 DM candidate. The thermal averaged s channel annihilation cross-sections are computed in appendix B.2 and are given in (B.13)–(B.17). The t channel thermalized annihilation cross-section to the pair of pseudo-scalars is given in equation (B.18).

We are now well equipped to calculate the present day relic abundance of DM by solving the Boltzmann equation:

$$\frac{dn_{\text{DM}}}{dt} + 3Hn_{\text{DM}} = -\langle\sigma|v|\rangle \left((n_{\text{DM}})^2 - (n_{\text{DM}}^{\text{EQ}})^2 \right) \quad (3.1)$$

where $H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi\rho}{3M_{\text{Pl}}^2}}$, $\langle\sigma|v|\rangle$ is the thermally averaged cross-section and $n_{\text{DM}}^{\text{EQ}} = g \left(\frac{m_{\text{DM}} T}{2\pi} \right)^{3/2} \exp \left(\frac{-m_{\text{DM}}}{T} \right)$ where the number of degrees of freedom g are 1, 2 and 3 for scalar, fermionic and vector DM respectively. The freeze-out occurred when DM is non-relativistic with $v \ll c$ and then $\langle\sigma|v|\rangle$ can be written as $\langle\sigma|v|\rangle = a + b v^2 + \mathcal{O}(v^4)$.

The Boltzmann equation is solved numerically following the reference [31] to give the thermal relic density

$$\Omega_{\text{DM}} h^2 \simeq \frac{1.07 \times 10^9 x_F}{M_{\text{Pl}} \sqrt{g^*(x_F)} \left(a + \frac{6b}{x_F} \right)} \quad (3.2)$$

where $g^*(x_F)$ is the total number of effective degrees of freedom at the freeze-out temperature T_F and $x_F = m_{\text{DM}}/T_F$ is obtained by solving

$$x_F = \ln \left[C(C+2) \sqrt{\frac{45}{g}} \frac{M_{\text{Pl}} m_{\text{DM}} \left(a + \frac{6b}{x_F} \right)}{2\pi^3 \sqrt{g^*(x_F)} \sqrt{x_F}} \right] \quad (3.3)$$

where C is of order 1. For the Dirac fermionic DM, the additional contribution from the anti-particle will make the $\Omega_{\text{DM}} h^2$ twice of that is given in equation (3.2).

We compute the relic density numerically using MadDM [32, 33], which require the pair annihilation cross-sections to be calculated by the event generator MadEvent [34, 35]. We have generated the input model files containing all the Feynman rules from the Lagrangian given in equations (2.5)–(2.9), (2.10a) and (2.10b) for the MadEvent using FeynRules [36, 37].

To analyse and study the model we consider a single DM candidate with a specific intrinsic spin quantum number associated with a given portal at a time. In other words, all DM-portal couplings bar the one under discussion shall be switched off to zero. To keep our calculation in compliance with the LHC data, we use the central values of the portal-VLQ coupling y_{ϕ^0} (y_{A^0}) for a given m_ψ and the portal mass m_{ϕ^0} (m_{A^0}) as computed from the experimental cross-section curves for the gauge-boson production at ATLAS [1–3] and given in the figures 4a and 4b respectively.

We have verified analytically the relic DM abundance by taking $g^*(x_F) = 92$ and $C = 1/2$ in equations (3.2) and (3.3) and found them to be in agreement with the numerical calculations done by MadDM.

In figure 5a, we depict the contours (for the scalar portal mass of 270 GeV and VLQ masses 0.4, 0.8, 1.2 and 1.6 TeV) in the plane defined by the varying scalar DM mass between 0.02–4.0 TeV and the scalar portal-scalar DM coupling $\kappa_{\eta\phi^0}$ which generate the correct amount of present day energy density for the scalar DM. In figure 5b, we show the variation of relic density ~ 0.11 curves corresponding to the three scalar portal masses 270, 500 and 750 GeV for a fixed VLQ mass of 400 GeV. In figures 5c and 5d we plot the relic density ~ 0.11 contours in the plane defined by the varying vector DM mass between 0.02–4.0 TeV and the scalar portal-vector DM coupling $\kappa_{V^0\phi^0}$ for the values of portal and VLQ masses. These contours are evaluated corresponding $v_\Phi = 1$ TeV. In figures 6a and 6c we plot the constant relic density contours for the fermionic DM in the plane defined by the DM mass and DM-portal coupling w.r.t. corresponding to the scalar and pseudo-scalar portals respectively. Three contours in figures 5b, 5d, 6b and 6d correspond to the three choices of the portal masses 270, 500 and 750 GeV respectively. We observe that

- the unshaded region below the curve is disallowed as it would over-close the universe with the DM. The perturbativity requirement that the coupling should be less than $\sqrt{4\pi}$ further shrinks the allowed parameter region.
- the pair annihilation cross-section on varying with DM mass maximizes at the DM mass $m_{\phi^0}/2$ for which the constant relic density contours drop sharply w.r.t. the coupling. The sharp fall in the constant relic density contours are again observed at the two different values of DM masses a) first at DM mass $\approx m_\psi$ where the portal mediated s channel pair annihilation process opens up for the pair production of VLQ's and b) then at DM mass $\approx m_{\phi^0}$ (m_{A^0}) where DM mediated t channel annihilation process opens up for pair production of portal scalars (pseudo-scalars) respectively.
- the relic density curve corresponding to the lowest VLQ mass spans the minimal allowed region as depicted *via* blue shaded region in figures 5 and 6. Increasing the mass of VLQ requires its coupling with the portal to be large so that it is consistent

with the gauge Boson pair production at LHC, which in turn pull down the DM-portal coupling to a much lower value such that enough relic density is generated. Therefore, the contribution of the DM greater than 1 TeV to the relic density can be made favourable with the choice of high VLQ masses > 400 GeV.

- the absence of the portal VEV dependence in the interaction Lagrangian of the fermionic DM renders its coupling with the portal to be more sensitive. The portal coupling with the DM are found to be an order of magnitude higher than the scalar and vector DM for an appreciable range of DM mass to generate the same relic density. Consequently, the allowed parameter region for which the perturbativity is satisfied becomes highly constrained.

We have performed the rest of our analysis with the conservative choice for VLQ mass of 400 GeV, corresponding to the three choices of portal masses 270, 500 and 750 GeV.

3.2 Indirect detection: monochromatic gamma rays

DM annihilation to SM photons (high energy gamma rays) in galactic halos can be generated from various astrophysical targets for example the Dwarf Spheroidal galaxies, Galactic centre and Galaxy clusters [12, 13, 38]. These gamma rays can travel galactic distances and their flux can be observed by the satellite based γ ray observatory Fermi-LAT [12, 13] and the ground-based Cherenkov telescope H.E.S.S. [14, 15]. The annihilation rates are roughly velocity independent in the non-relativistic region. Here in particular we compare the bounds from the indirect detection experiments in the $\gamma\gamma$ and γZ channels.

In our model, the production of the monochromatic photons are realised in the DM pair annihilation to $\gamma\gamma$ and γZ two body final states. These processes are studied in the context of the scalar portal induced interactions for the scalar, vector and fermionic DM candidates while the pseudo-scalar induced interactions are only allowed for spin 1/2 DM candidates. We can directly use the thermal averaged cross sections which are expressed in terms of the local velocity of the DM particle in the appendix B. We analyse the variation of the thermal averaged DM annihilation cross-sections to $\gamma\gamma$ and γZ w.r.t. the DM mass in detail for all the cases and are depicted in the figures 7 and 8. To calculate the thermal averaged cross-section for the indirect detection we shall use the conservative lower bound on the DM-portal effective coupling obtained from the relic density criterion for a given DM mass. Therefore, the region below the curves defined in the DM mass and DM-portal coupling plane become cosmologically disfavoured. We plot and compare our results in the $\gamma\gamma$ mode with the limits obtained from Fermi-LAT [13], for the restricted DM mass range (< 500 GeV).

We find that the model calculated thermal averaged DM pair annihilation cross-section in the $\gamma\gamma$ channel lies below the limit obtained from the experimental results for an appreciable range of DM mass. The region trapped between the experimental curve and our results from the top and below respectively depicts the allowed region of the thermal averaged cross-section, which can further be translated in terms of the allowed model parameter space w.r.t. relic density and the indirect detection. Therefore the indirect experimental results naturally provides the upper bound on the coupling, for a given DM mass. We note

Figure 7. Figures 7a and 7b depict the thermal averaged cross-sections for scalar DM pair annihilation $\eta\eta \rightarrow \phi^0 \rightarrow \gamma\gamma$ and $\eta\eta \rightarrow \phi^0 \rightarrow \gamma Z$ processes *via* scalar portal respectively. Figures 7c and 7d show the thermal averaged cross-sections for vector DM pair annihilation $V^0V^0 \rightarrow \phi^0 \rightarrow \gamma\gamma$ and $V^0V^0 \rightarrow \phi^0 \rightarrow \gamma Z$ processes *via* scalar portal respectively. All the cross-sections are drawn for the upper limit on DM couplings allowed by the relic density constraints for a given DM mass. We have also exhibited the Fermi-LAT 1 σ and 2 σ limits for DM mass range < 500 GeV [13] and H.E.S.S. 2013 upper limit on the thermal averaged cross-section for DM mass range > 500 GeV [15] corresponding to $\gamma\gamma$ and γZ channels. Shaded regions appearing in blue, golden yellow and red correspond to the relic density forbidden regions for the portal mass of 270, 500 and 750 GeV respectively.

that the $\langle\sigma(\chi\bar{\chi} \rightarrow \phi^0 \rightarrow \gamma\gamma) v\rangle$ is p -wave suppressed and therefore lies much below than that of the null result obtained from the FermiLAT.

3.3 Direct detection

Direct detection of the DM identifies the nature of the low-energy effective DM-nucleon scattering interaction. Therefore, the direct detection experiments aim to establish a first confirmed detection of DM particles. Direct detection data analysis focuses on formulation and computation of the momentum (energy) and velocity dependent cross-section scenarios, where DM couples to target nuclei by spin-independent or spin-dependent interactions. Spin-independent cross-section scales coherently with the nucleon number, so nuclei of

Figure 8. Figures 8a and 8b depict the thermal averaged cross-sections for fermionic DM pair annihilation $\chi\bar{\chi} \rightarrow \phi^0 \rightarrow \gamma\gamma$ and $\chi\bar{\chi} \rightarrow \phi^0 \rightarrow \gamma Z$ processes *via* scalar portal respectively. Figures 8c and 8d show the thermal averaged cross-sections for fermionic DM pair annihilation $\chi\bar{\chi} \rightarrow A^0 \rightarrow \gamma\gamma$ and $\chi\bar{\chi} \rightarrow A^0 \rightarrow \gamma Z$ processes *via* pseudo-scalar portal respectively. All the cross-sections are drawn for the upper limit on DM couplings allowed by the relic density constraints for a given DM mass. We have also exhibited the Fermi-LAT 1 σ and 2 σ limits for DM mass range < 500 GeV [13] and H.E.S.S. 2013 upper limit on the thermal averaged cross-section for DM mass range > 500 GeV [15] corresponding to $\gamma\gamma$ and γZ channels. Shaded regions appearing in blue, golden yellow and red correspond to the relic density forbidden regions for the portal masses of 270, 500 and 750 GeV respectively.

larger atomic mass are always more effective in the direct detection searches. The spin-dependent scattering cross-section on the other hand is most effectively probed by a nucleus with larger spin.

Direct detection experiments Dark-Side50 [16], LUX [17, 18, 21], XENON1T [19] etc. are set to observe the recoil energy transferred to target nucleus in an elastic collision with the DM particles. The current experimental null results [19], constrain the maximum value of the elastic nucleon-DM cross-sections. The constraints on the upper limit of the elastic cross-sections will be considerably lowered in the future projected sensitivities of the super CDMS experiments [39].

The elastic scattering of DM particles η , V^0 and χ from a heavy nucleus can be illustrated in terms of the effective DM scattering off the gluons, where the DM is attached to

Figure 9. DM-Nucleon scattering diagram induced by the portal-VLQ loop interaction.

the triangle loop of charged virtual VLQ *via* the portal which in turn interacts with the nucleons via two gluons exchange. Since, this occurs at very low energy and momentum $\lesssim \mathcal{O}(1)$ GeV, all the propagators are approximated by their respective masses. The nucleus recoil which is of the order of few MeV is then measured in the detector. DM particles scatter-off nucleons through the t channel exchange of portal scalar and the scattering of gluons *via* triangle VLQ loop, gives the dominant contribution to the DM-nucleon scattering cross-section. The scalar gluon-gluon coupling is described by the effective Lagrangian given in (2.9a) and (2.9b) as

$$\mathcal{L}_{\phi^0 gg}^{\text{eff}} = \frac{y_{\phi^0}}{m_{\psi}} \frac{\alpha_s(m_{\phi^0})}{12\pi} 3I_{gg} G_{\mu\nu}^a G_{\mu\nu}^a \phi^0, \quad (3.4)$$

where the loop integral I_{gg} is given in appendix A. The effective DM-gluon interaction can be described by the effective Lagrangian

$$\mathcal{L}_{\text{eff}}^{\eta gg} = \frac{\alpha_s(m_{\phi^0}) v_{\Phi} \kappa_{\eta\phi^0} y_{\phi^0}}{24\pi m_{\phi^0}^2 m_{\psi}} (3I_{gg}) \eta \eta G_{\mu\nu}^a G_a^{\mu\nu} \quad (3.5)$$

through the Feynman diagram given in figure 9. This interaction contributes to the spin-independent part of the DM- nucleon scattering cross-section to give

$$\sigma_{\text{SI}}(\eta N \rightarrow \eta N) = \frac{1}{729\pi} \frac{y_{\phi^0}^2 v_{\Phi}^2 \kappa_{\eta\phi^0}^2 \mu_{N\eta}^2 m_N^2}{2 m_{\eta}^2 m_{\phi^0}^4 m_{\psi}^2} \left(\frac{\alpha_s(m_{\phi^0})}{\alpha_s(m_H)} \right)^2 (3I_{gg})^2 (f_{\text{TG}}^N)^2 \quad (3.6)$$

where $\mu_{N\eta} = \frac{m_N m_{\eta}}{(m_{\eta} + m_N)}$ is the nucleon-DM reduced mass and $f_{\text{TG}}^N \equiv -\frac{9\alpha_s(\mu)}{m_N 8\pi} \langle N | O_g | N \rangle$ is the gluon contribution to the zero-momentum hadronic matrix element. f_{TG}^N can be extracted in terms of light quark contribution to the zero-momentum hadronic matrix element as

$$f_{\text{TG}}^N = 1 - \sum_{q=u,d,s} f_{Tq}^N \equiv 1 - \sum_{q=u,d,s} \frac{1}{m_N} \langle N | O_q | N \rangle. \quad (3.7)$$

Here the hadronic matrix element refers to a definite spin state of the nucleon. The f_{TG}^N is calculated to be 0.92 using the values for f_{Tq}^N quoted in the literature [27, 40–42].

We estimate the direct detection cross-section using the central value of y_{ϕ^0} obtained from the LHC for a given portal scalar mass and $m_\psi = 400$ GeV along with the cosmologically allowed lower bound on the DM-scalar portal coupling for a given DM mass. The variation of the scalar DM-Nucleon scattering cross-section *via* scalar portal is depicted in the figure 10a corresponding to the three scalar portal masses 270, 500 and 750 GeV respectively.

On the similar note, the spin-independent cross-sections for the vector and fermionic dark matter interaction *via* the scalar mediator are given by

$$\sigma_{\text{SI}}(\chi N \rightarrow \chi N) = \frac{2 m_N^2 \mu_{N\chi}^2}{\pi} \frac{\kappa_{\chi\phi^0}^2 y_{\phi^0}^2}{729 m_{\phi^0}^4 m_\psi^2} \left(\frac{\alpha_s(m_{\phi^0})}{\alpha_s(m_H)} \right)^2 (3 I_{gg})^2 (f_{\text{TG}}^N)^2 \quad (3.8)$$

$$\sigma_{\text{SI}}(V^0 N \rightarrow V^0 N) = \frac{\mu_{NV^0}^2 m_N^2}{2\pi} \frac{\kappa_{V^0\phi^0}^2 v_\Phi^2 y_{\phi^0}^2}{729 m_{V^0}^2 m_{\phi^0}^4 m_\psi^2} \left(\frac{\alpha_s(m_{\phi^0})}{\alpha_s(m_H)} \right)^2 (3 I_{gg})^2 (f_{\text{TG}}^N)^2 \quad (3.9)$$

respectively where $\mu_{N\chi} = \frac{m_N m_\chi}{m_N + m_\chi}$ and $\mu_{NV^0} = \frac{m_N m_{V^0}}{m_N + m_{V^0}}$. The variation of the vector and fermionic DM-nucleon scattering cross-sections *via* scalar portal are depicted in the figures 10b and 10c respectively. Each figure depicts the scattering cross-section for three scalar portal masses 270, 500 and 750 GeV respectively.

On comparison we find that for the most of the DM mass range our direct detection cross-section curves in figures 10a, 10b and 10c lie much below the null result of the experiment [19] which in turn gives an upper bound on the DM -portal coupling for a given DM mass and thus constrains the portal induced DM parameter space. We note that the scalar and vector DM scattering cross-section is an order of magnitude higher than that of the fermionic DM contribution. Thus the DM scattering experimental constraints do not shrink the allowed parameter space for the fermionic DM below the mass region 300 GeV which is in contrary to the scalar and vector DM contributions.

For the direct detection cross-section induced by the CP odd pseudo-scalar mediator the corresponding $A^0 g g$ coupling and the effective DM-gluon interaction is given by

$$\mathcal{L}_{A^0 g g}^{\text{eff}} = \frac{y_{A^0}}{m_\psi} \frac{\alpha_s(m_{A^0})}{8\pi} 2 \tilde{I}_{gg} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a A^0 \quad (3.10)$$

$$\mathcal{L}_{\text{eff}}^{\chi\chi gg} = i \kappa_{\chi A^0} y_{A^0} \frac{1}{m_{A^0}^2 m_\psi} \frac{\alpha_s}{\pi} \tilde{I}_{gg} \bar{\chi} \gamma_5 \chi G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}. \quad (3.11)$$

The effective Lagrangian (3.11) generates a spin-dependent DM-nucleon cross-section which is however suppressed by the square of the momentum exchanged and is therefore sub-dominant. The available experimental results on the spin-dependent cross-sections are comparatively less tightly constrained [18, 21, 43], hence not shown graphically.

4 Summary and conclusions

Our analysis provide a conservative complementary scenario to that appeared in the review [24], where we have neglected the portal mixing with the SM Higgs and instead we have generated the required relic density of DM by considering an effective loop induced interaction of the VLQ with the portal.

Figure 10. The spin-independent DM-nucleon elastic cross-sections are depicted as a function of DM mass for the scalar, vector and fermionic dark matter in figures 10a, 10b and 10c respectively. In each of the figure three graphs are exhibited for the fixed VLQ mass 400 GeV and scalar portal masses 270, 500, 750 GeV respectively. All the cross-sections are drawn for the upper limit on the respective DM couplings allowed by the relic density constraints for a given DM mass. We have also exhibited the experimental cross-section from LUX (2017) [17, 18], XENON (2017) [19] and Dark-Side50 (2016) [16]. Shaded regions appearing in blue, golden yellow and red correspond to the relic density forbidden regions for the portal masses of 270, 500 and 750 GeV respectively.

In this paper we considered a $U(1)_d$ extension of the standard model with a dark sector and a singlet scalar or a pseudo-scalar di-Boson resonance which interacts with the SM gauge Bosons through a vector-like SM colour triplet fermion of exotic charge $Q = 5/3$. The dark matter particle considered here is a neutral SM singlet real scalar, a real vector or a spin-1/2 fermion interacting with the standard model gauge Bosons through a scalar/pseudo-scalar di-Boson resonance. As a first step we obtained the constraints on the coupling of di-Boson resonance with the vector-like fermions from the ATLAS and CMS experimental searches through spin-zero di-photon production cross-section $\sigma(pp \rightarrow \phi^0/A^0 \rightarrow \gamma\gamma)$. The constrained parameter region in $(y_{\phi^0/A^0} - m_\psi)$ plane is depicted in figure 4 at the 2σ level. With these constraints in place, we obtained relic density contours in the dark matter mass-coupling parameter space assuming that the dark matter particles considered here saturate the observed relic density $\Omega_c h^2 \simeq 0.1138 \pm .0045$. We then study

Figure 11. All model constraints are drawn for the portal mass of 270 GeV and VLQ mass 400 GeV. The shaded region correspond to the forbidden regions by relic density [28, 30] (green), XENON1T 2017 [19] (blue), PANDA 2017 [21] (indigo), Fermi-LAT [13] (pink), H.E.S.S. [15] (red) and the perturbativity condition (golden yellow) respectively in the plane defined by $m_\eta - \kappa_{\eta\phi^0}$, $m_{V^0} - \kappa_{V^0\phi^0}$, $m_\chi - \kappa_{\chi\phi^0}$ and $m_\chi - \kappa_{\chi A^0}$ in figures 11a, 11b, 11c, and 11d respectively. Constraint from the direct detection experiments for the pseudo-scalar portal are not shown (see text).

that the prediction of the LHC and relic density constrained model for a) the air-borne indirect detection of DM pair annihilation into a pair of $\gamma\gamma/\gamma Z$ in the galactic halo and b) the ground based DM-nucleon scattering direct detection experiments.

On comparing the thermal averaged annihilation cross-sections for the indirect detection with the limits on the cross-section obtained from the Fermi-LAT and H.E.S.S. (2013) in the mass range less and greater than 500 GeV respectively through the observation of monochromatic gamma-rays, we found that the model predicted annihilation cross-section with the allowed lower bound of scalar/vector-scalar portal and fermionic DM-pseudo-scalar portal couplings are being favoured by the limits obtained from these experiments for the DM masses 400 GeV and above as shown in figures 7, 8c and 8d. However, the model prediction of the annihilation cross-section for fermionic DM induced by the scalar portal lies far below the experimental upper limit and therefore favours the large model parameter space spanning the mass range upto 4 TeV as shown in the figures 8a and 8b.

Figure 12. All model constraints are drawn for the portal mass of 500 GeV and VLQ mass 400 GeV. The shaded region correspond to the forbidden regions by relic density [28, 30] (green), XENON1T 2017 [19] (blue), PANDA 2017 [21] (indigo), Fermi-LAT [13] (pink), H.E.S.S. [15] (red) and the perturbativity condition (golden yellow) respectively in the plane defined by $m_\eta - \kappa_\eta \phi^0$, $m_{V^0} - \kappa_{V^0} \phi^0$, $m_\chi - \kappa_\chi \phi^0$ and $m_\chi - \kappa_\chi A^0$ in figures 12a, 12b, 12c, and 12d respectively. Constraints from the direct detection experiments for the pseudo-scalar portal are not shown (see text).

Comparing the constrained model prediction for spin-independent direct detection DM-nucleon elastic scattering experiments with the recent experimental results from LUX (2016) [17], XENON1T (2017) [19], PANDA (2017) [21] and Dark-Side50 (2016) [16] collaborations as shown in figures 10a, 10b and 10c respectively, we find that almost the entire parameter space allowed by the LHC searches and the observed relic density is also allowed by the direct detection experiments for the fermionic dark matter. The case of real scalar and vector dark matter particles is different, where the parameter region is favoured only for the mass range greater than 300 GeV.

Finally, it is important to comment upon the model restrictions, if it has to satisfy each and every experimental results. This helps in narrowing down the search for such DM candidates in the ongoing and upcoming collider based experiments. To this end we translate the experimental results in terms of restriction on the DM mass and DM-portal coupling for the mass range varying between 10 GeV and 4 TeV. Therefore, we summarise

Figure 13. All model constraints are drawn for the portal mass of 750 GeV and VLQ mass 400 GeV. The shaded region correspond to the forbidden regions by relic density [28, 30] (green), XENON1T 2017 [19] (blue), PANDA 2017 [21] (indigo), Fermi-LAT [13] (pink), H.E.S.S. [15] (red) and the perturbativity condition (golden yellow) respectively in the plane defined by $m_\eta - \kappa_{\eta\phi^0}$, $m_{V^0} - \kappa_{V^0\phi^0}$, $m_\chi - \kappa_{\chi\phi^0}$ and $m_\chi - \kappa_{\chi A^0}$ in figures 13a, 13b, 13c, and 13d respectively. Constraints from the direct detection experiments for the pseudo-scalar portal are not shown (see text).

our analysis with the help of the three composite figures 11, 12 and 13 corresponding to the three choice of the scalar portal masses 270, 500 and 750 GeV respectively, where we have put all the constraints from the relic density, two indirect detection experiments and two direct detection experiments on the model for a specific DM candidate in a plane spanned by its mass and coupling to the scalar and/or pseudo-scalar portal. These figures spell out the implications of the experimental results on the model parameter space and depict

- the contours drawn with the coordinates of the lower limit on the DM-portal coupling for a given DM mass derived from the constant relic density [28, 30]
- the contours drawn with the coordinates of the upper limit on the respective DM-portal coupling for a given DM mass by demanding such DM candidates to satisfy the observed null results of the thermal averaged pair production cross-section for $\gamma\gamma$ final state due to a DM pair annihilation from Fermi-LAT [13] (H.E.S.S. 2013 [15]) for DM mass range less (greater) than 500 GeV.

- the contours drawn with the coordinates of the upper limit on the respective DM-portal coupling for a given DM mass by demanding such DM candidates to satisfy the observed null results of the sensitive DM-nucleon scattering cross-section from the recent experiments XENON1T (2017) [19] and PANDA (2017) [21]. However, since we do not have a stringent experimental constraints on the spin dependant fermionic DM-nucleon cross-sections, we do not show any direct detection contours for the pseudo-scalar induced fermionic DM.

It is remarkable to note that we have now shrunk the allowed parameter space which appear as white unshaded region in each of these figures. However, area of the allowed unshaded white region in figures 11–13 for the DM masses greater than 1 TeV can be enhanced by increasing the VLQ mass above 400 GeV. Thus this tightly constrained spin $0^\pm$ induced DM model has become challenging enough to be probed in the colliders.

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A Partial decay-widths of the scalar/pseudo-scalar portal with effective vertices

Using the Lagrangian given in equations (2.5)–(2.9), we calculate the effective strength of the interactions involving SM neutral gauge Bosons and the scalar or pseudo-scalar portal. These effective interactions are computed by evaluating the triangle VLQ loop integrals in the heavy fermion limit.

The effective couplings for the scalar portal are expressed as

$$\kappa_{gg} = \frac{y_{\phi^0}}{m_\psi} \frac{\alpha_s(m_{\phi^0})}{4\pi} I_{gg} \quad (\text{A.1a})$$

$$\kappa_{\gamma\gamma} = \frac{y_{\phi^0}}{m_\psi} \frac{\alpha_{\text{em}}(0)}{2\pi} N_c Q_\psi^2 I_{\gamma\gamma} \quad (\text{A.1b})$$

$$\kappa_{\gamma Z} = \frac{y_{\phi^0}}{m_\psi} \frac{\alpha_{\text{em}}(0)}{\pi} N_c Q_\psi^2 \tan \theta_W I_{\gamma Z} \quad (\text{A.1c})$$

$$\kappa_{ZZ} = \frac{y_{\phi^0}}{m_\psi} \frac{\alpha_{\text{em}}(0)}{2\pi} N_c Q_\psi^2 \tan^2 \theta_W I_{ZZ} \quad (\text{A.1d})$$

corresponding to the $\phi^0 g g$, $\phi^0 \gamma \gamma$, $\phi^0 \gamma Z$ and $\phi^0 Z Z$ effective vertices. The respective loop integrals are given as

$$I_{gg} = I_{\gamma\gamma} = \int_0^1 dx \int_0^{1-x} dy \frac{f(x, y)}{1 - \frac{m_{\phi^0}^2}{m_\psi^2} x y} \quad (\text{A.2a})$$

$$I_{\gamma Z} = \int_0^1 dx \int_0^{1-x} dy \frac{f(x, y)}{1 - \left(\frac{m_{\phi^0}^2}{m_\psi^2} - \frac{m_Z^2}{m_\psi^2} \right) x y - x(1-x) \frac{m_Z^2}{m_\psi^2}} \quad (\text{A.2b})$$

$$I_{ZZ} = \int_0^1 dx \int_0^{1-x} dy \frac{f(x, y)}{1 - \left(\frac{m_{\phi^0}^2}{m_{\psi}^2} - 2 \frac{m_Z^2}{m_{\psi}^2} \right) x y - \{x(1-x) + y(1-y)\} \frac{m_Z^2}{m_{\psi}^2}} \quad (\text{A.2c})$$

where $f(x, y) = (1 - 4xy)$.

The partial decay-widths of the scalar portal to the SM neutral gauge Bosons are computed and are given as

$$\Gamma(\phi^0 \rightarrow gg) = \frac{y_{\phi^0}^2}{8\pi} m_{\phi^0} \left(\frac{\alpha_s(m_{\phi^0})}{\pi} \right)^2 \frac{m_{\phi^0}^2}{m_{\psi}^2} |I_{gg}|^2 \quad (\text{A.3a})$$

$$\Gamma(\phi^0 \rightarrow \gamma\gamma) = \frac{y_{\phi^0}^2}{16\pi} m_{\phi^0} \left(\frac{\alpha_{\text{em}}(0)}{\pi} \right)^2 \frac{m_{\phi^0}^2}{m_{\psi}^2} N_c^2 Q_{\psi}^4 |I_{\gamma\gamma}|^2 \quad (\text{A.3b})$$

$$\Gamma(\phi^0 \rightarrow Z\gamma) = \frac{y_{\phi^0}^2}{8\pi} m_{\phi^0} \left(\frac{\alpha_{\text{em}}(0)}{\pi} \right)^2 \frac{m_{\phi^0}^2}{m_{\psi}^2} N_c^2 Q_{\psi}^4 \tan^2 \theta_W \left(1 - \frac{m_Z^2}{m_{\phi^0}^2} \right)^3 |I_{\gamma Z}|^2 \quad (\text{A.3c})$$

$$\begin{aligned} \Gamma(\phi^0 \rightarrow ZZ) &= \frac{y_{\phi^0}^2}{16\pi} m_{\phi^0} \left(\frac{\alpha_{\text{em}}(0)}{\pi} \right)^2 \frac{m_{\phi^0}^2}{m_{\psi}^2} N_c^2 Q_{\psi}^4 \tan^4 \theta_W \left(1 - 4 \frac{m_Z^2}{m_{\phi^0}^2} \right)^{1/2} \\ &\times \left(1 - 4 \frac{m_Z^2}{m_{\phi^0}^2} + 6 \frac{m_Z^4}{m_{\phi^0}^4} \right) |I_{ZZ}|^2 \end{aligned} \quad (\text{A.3d})$$

The expression for $\Gamma(\phi^0 \rightarrow ZZ)$ is correct to $\sim 0.1\%$.

Similarly, the effective couplings $\tilde{\kappa}_{VV}$ of the pseudo-scalar to the pair of $gg, \gamma\gamma, \gamma Z$ and ZZ are obtained by replacing $y_{\phi^0} \rightarrow y_{A^0}, m_{\phi^0} \rightarrow m_{A^0}$ and $I_{VV} \rightarrow \tilde{I}_{VV}$ in equations (A.1a)–(A.1d) respectively. The corresponding loop integrals $\tilde{I}_{VV}$ are obtained by substituting $m_{\phi^0} \rightarrow m_{A^0}$ and $f(x, y)$ by 1 in equations (A.2a)–(A.2c) respectively. Accordingly, the partial decay-widths of the pseudo-scalar to a pair of SM neutral gauge Bosons can be obtained by replacing y_{ϕ^0} by y_{A^0}, m_{ϕ^0} by m_{A^0} and I_{VV} by $\tilde{I}_{VV}$ in equations (A.3a)–(A.3d).

B Thermal averaged DM pair annihilation cross-sections

B.1 Scalar portal

The thermal averaged cross-sections for the annihilation of scalar DM to SM gauge Bosons are given as

$$\left\langle \sigma_{\eta\eta \rightarrow gg}^{\phi^0} v_{\text{rel}} \right\rangle = \frac{1}{\pi} \frac{\kappa_{\eta\phi^0}^2 v_{\Phi}^2}{(4m_{\eta}^2 - m_{\phi^0}^2)^2 + \Gamma_{\phi^0}^2 m_{\phi^0}^2} \frac{\alpha_s^2 y_{\phi^0}^2 I_{gg}^2}{\pi^2} \frac{m_{\eta}^2}{m_{\psi}^2} \quad (\text{B.1})$$

$$\left\langle \sigma_{\eta\eta \rightarrow \gamma\gamma}^{\phi^0} v_{\text{rel}} \right\rangle = \frac{1}{2\pi} \frac{\kappa_{\eta\phi^0}^2 v_{\Phi}^2}{(4m_{\eta}^2 - m_{\phi^0}^2)^2 + \Gamma_{\phi^0}^2 m_{\phi^0}^2} \frac{\alpha_{\text{em}}^2 y_{\phi^0}^2 I_{\gamma\gamma}^2}{\pi^2} \frac{m_{\eta}^2}{m_{\psi}^2} N_c^2 Q_{\psi}^4 \quad (\text{B.2})$$

$$\begin{aligned} \left\langle \sigma_{\eta\eta \rightarrow Z\gamma}^{\phi^0} v_{\text{rel}} \right\rangle &= \frac{1}{\pi} \frac{\kappa_{\eta\phi^0}^2 v_{\Phi}^2}{(4m_{\eta}^2 - m_{\phi^0}^2)^2 + \Gamma_{\phi^0}^2 m_{\phi^0}^2} \frac{\alpha_{\text{em}}^2 y_{\phi^0}^2 I_{\gamma Z}^2}{\pi^2} \frac{m_{\eta}^2}{m_{\psi}^2} N_c^2 Q_{\psi}^4 \\ &\times \tan^2 \theta_W \left(1 - \frac{m_Z^2}{4m_{\eta}^2} \right)^3 \end{aligned} \quad (\text{B.3})$$

$$\begin{aligned} \left\langle \sigma_{\eta\eta \rightarrow ZZ}^{\phi^0} v_{\text{rel}} \right\rangle &= \frac{1}{2\pi} \frac{\kappa_{\eta\phi^0}^2 v_\Phi^2}{(4m_\eta^2 - m_{\phi^0}^2)^2 + \Gamma_{\phi^0}^2 m_{\phi^0}^2} \frac{\alpha_{\text{em}}^2 y_{\phi^0}^2 I_{ZZ}^2}{\pi^2} \frac{m_\eta^2}{m_\psi^2} N_c^2 Q_\psi^4 \tan^4 \theta_W \\ &\times \left[\frac{3m_Z^4}{8m_\eta^4} - \frac{m_Z^2}{m_\eta^2} + 1 \right] \left(1 - \frac{m_Z^2}{m_\eta^2} \right)^{1/2} \end{aligned} \quad (\text{B.4})$$

$$\left\langle \sigma_{\eta\eta \rightarrow \psi\psi}^{\phi^0} v_{\text{rel}} \right\rangle = \frac{y_{\phi^0}^2 \kappa_{\eta\phi^0}^2 v_\Phi^2}{4\pi m_\eta^3} \frac{(m_\eta^2 - m_\psi^2)^{3/2}}{16(m_\eta^2 - m_{\phi^0}^2)^2} \quad (\text{B.5})$$

$$\left\langle \sigma_{\eta\eta \rightarrow \phi^0\phi^0} v_{\text{rel}} \right\rangle \simeq \frac{\kappa_{\eta\phi^0}^4 v_\Phi^4 \left(1 - \frac{m_{\phi^0}^2}{2m_\eta^2} \right)}{16\pi m_\eta^6} \quad (\text{B.6})$$

The thermal averaged cross-sections for the annihilation of the vector DM pair via scalar portal to the di-Boson final states can be directly read out from the corresponding expressions for the scalar DM modulo the spin averaging of the initial states and the polarisation sum involved in the matrix element squared. We obtain the pair annihilation cross-section to the respective final states directly by substituting $\kappa_{\eta\phi^0}$ by $\kappa_{V^0\phi^0}/3$ and m_η by m_{V^0} in equations (B.1)–(B.4). The thermal averaged cross-section for the s channel process $\langle \sigma(V^0 V^0 \rightarrow \bar{\psi}\psi) v \rangle$ is computed to be 1/6 of the $\langle \sigma(\eta\eta \rightarrow \bar{\psi}\psi) v \rangle$ given in (B.5). The thermal averaged cross-section for t -channel pair is identical to that of the scalar DM annihilation to pair of scalar portals is given in (B.6).

The thermal averaged cross-sections for the annihilation of fermionic DM via scalar portal are given as

$$\left\langle \sigma_{\chi\chi \rightarrow gg}^{\phi^0} v_{\text{rel}} \right\rangle = \frac{\kappa_{\chi\phi^0}^2 y_{\phi^0}^2 \alpha_s^2}{2\pi^3 m_\psi^2} \frac{m_\chi^4 I_{gg}^2}{(4m_\chi^2 - m_{\phi^0}^2)^2 + \Gamma_{\phi^0}^2 m_{\phi^0}^2} \left(\frac{6}{x_F} \right) \quad (\text{B.7})$$

$$\left\langle \sigma_{\chi\chi \rightarrow \gamma\gamma}^{\phi^0} v_{\text{rel}} \right\rangle = \frac{\kappa_{\chi\phi^0}^2 y_{\phi^0}^2 \alpha_{\text{em}}^2}{4\pi^3 m_\psi^2} \frac{m_\chi^4 I_{\gamma\gamma}^2}{(4m_\chi^2 - m_{\phi^0}^2)^2 + \Gamma_{\phi^0}^2 m_{\phi^0}^2} N_c^2 Q_\psi^4 \left(\frac{6}{x_F} \right) \quad (\text{B.8})$$

$$\begin{aligned} \left\langle \sigma_{\chi\chi \rightarrow Z\gamma}^{\phi^0} v_{\text{rel}} \right\rangle &= \frac{\kappa_{\chi\phi^0}^2 y_{\phi^0}^2 \alpha_{\text{em}}^2}{2\pi^3 m_\psi^2} \frac{m_\chi^4 I_{\gamma Z}^2}{(4m_\chi^2 - m_{\phi^0}^2)^2 + \Gamma_{\phi^0}^2 m_{\phi^0}^2} \left(1 - \frac{m_Z^2}{4m_V^2} \right)^3 \\ &\times \tan^2 \theta_W N_c^2 Q_\psi^4 \left(\frac{6}{x_F} \right) \end{aligned} \quad (\text{B.9})$$

$$\begin{aligned} \left\langle \sigma_{\chi\chi \rightarrow ZZ}^{\phi^0} v_{\text{rel}} \right\rangle &= \frac{\kappa_{\chi\phi^0}^2 y_{\phi^0}^2 \alpha_{\text{em}}^2}{4\pi^3 m_\psi^2} \frac{m_\chi^4 I_{ZZ}^2 \tan^4 \theta_W N_c^2 Q_\psi^4}{(4m_\chi^2 - m_{\phi^0}^2)^2 + \Gamma_{\phi^0}^2 m_{\phi^0}^2} \sqrt{1 - \frac{4m_Z^2}{s}} \\ &\times \left(1 - \frac{4m_Z^2}{m_{\phi^0}^2} + \frac{6m_Z^4}{m_{\phi^0}^4} \right) \left(\frac{6}{x_F} \right) \end{aligned} \quad (\text{B.10})$$

$$\left\langle \sigma_{\chi\chi \rightarrow \psi\psi}^{\phi^0} v_{\text{rel}} \right\rangle = \frac{y_{\phi^0}^2 \kappa_{\chi\phi^0}^2}{8\pi m_\chi} \frac{(m_\chi^2 - m_\psi^2)^{3/2}}{16(m_\chi^2 - m_{\phi^0}^2)^2} \left(\frac{6}{x_F} \right) \quad (\text{B.11})$$

$$\left\langle \sigma_{\bar{\chi}\chi \rightarrow \phi^0\phi^0} v_{\text{rel}} \right\rangle \simeq \frac{3\kappa_{\chi\phi^0}^4}{128\pi m_\chi^2} \left(\frac{6}{x_F} \right) \quad (\text{B.12})$$

B.2 Pseudo-scalar portal

The Thermal averaged cross-sections for the annihilation of fermionic DM via pseudo-scalar portal are given as

$$\langle \sigma_{\tilde{\chi}\chi \rightarrow gg}^{A^0} v_{\text{rel}} \rangle = \frac{2\alpha_s^2 \kappa_{\chi A^0}^2 y_{A^0}^2}{\pi^3 m_\psi^2} \frac{m_\chi^4}{(4m_\chi^2 - m_{A^0}^2)^2 + \Gamma_{A^0}^2 m_{A^0}^2} \tilde{I}_{gg}^2 \left(1 + \frac{15}{4x_F}\right) \quad (\text{B.13})$$

$$\langle \sigma_{\tilde{\chi}\chi \rightarrow \gamma\gamma}^{A^0} v_{\text{rel}} \rangle = \frac{\alpha_{\text{em}}^2 \kappa_{\chi A^0}^2 y_{A^0}^2}{\pi^3 m_\psi^2} \frac{m_\chi^4}{(4m_\chi^2 - m_{A^0}^2)^2 + \Gamma_{A^0}^2 m_{A^0}^2} \tilde{I}_{\gamma\gamma}^2 N_c^2 Q_\psi^4 \left(1 + \frac{15}{4x_F}\right) \quad (\text{B.14})$$

$$\begin{aligned} \langle \sigma_{\tilde{\chi}\chi \rightarrow Z\gamma}^{A^0} v_{\text{rel}} \rangle &= \frac{2\alpha_{\text{em}}^2 y_{A^0}^2 \kappa_{\chi A^0}^2}{\pi^3 m_\psi^2} \frac{m_\chi^4}{(4m_\chi^2 - m_{A^0}^2)^2 + \Gamma_{A^0}^2 m_{A^0}^2} \\ &\times \left(1 - \frac{m_Z^2}{4m_\chi^2}\right)^3 \tilde{I}_{\gamma Z}^2 N_c^2 Q_\psi^4 \tan^2 \theta_W \end{aligned} \quad (\text{B.15})$$

$$\begin{aligned} \langle \sigma_{\tilde{\chi}\chi \rightarrow ZZ}^{A^0} v_{\text{rel}} \rangle &= \frac{1}{8\pi} \sqrt{1 - 4\frac{m_{A^0}^2}{m_\chi^2}} \frac{y_{A^0}^2 \kappa_{\chi A^0}^2 \alpha_{\text{em}}^2}{\pi^2} \frac{m_\chi^2}{m_\psi^2} \frac{\tilde{I}_{ZZ}^2 N_c^2 Q_\psi^4 \tan^4 \theta_W}{(4m_\chi^2 - m_{A^0}^2)^2 + \Gamma_{A^0}^2 m_{A^0}^2} \\ &\times \left(1 - \frac{4m_Z^2}{m_{A^0}^2}\right)^{3/2} \end{aligned} \quad (\text{B.16})$$

$$\langle \sigma_{\tilde{\chi}\chi \rightarrow \psi\psi}^{A^0} v_{\text{rel}} \rangle = \frac{y_{A^0}^2 \kappa_{\chi A^0}^2}{2\pi} \frac{m_\chi (m_\chi^2 - m_\psi^2)^{1/2}}{16(m_\chi^2 - m_{A^0}^2)^2} \quad (\text{B.17})$$

$$\langle \sigma_{\tilde{\chi}\chi \rightarrow A^0 A^0} v_{\text{rel}} \rangle \simeq \frac{\kappa_{\chi A^0}^4 m_{A^0}^4}{320\pi m_\chi^6} \left(1 + \frac{3m_{A^0}^2}{10m_\chi^2}\right) \quad (\text{B.18})$$

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