Multicomponent Dark Matter from a Vector Field in the Fundamental Representation of $SU(2)_L$ and a singlet scalar field

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Abstract

In this work we explored an scenario where we considered a vector field in the fundamental representation of $SU(2)_L$ where the neutral CP-even component act as a Dark matter candidate and aditionally we introduced an extra scalar DM candidate. Within this multicomponent DM scenario we show that the relic abundance can be enhanced through the interaction of the extra scalar DM component in the region below the 840 GeV in comparison with the original model.

1 Introduction

2 The Model

In this work we introduce a multicomponent dark matter sector which comes from a vector doublet field V_μ in the fundamental representation of $SU(2)_L$ and an additional scalar singlet S. The new vector is odd under a discrete symmetry Z_2 and the new real scalar is odd under another discrete symmetry Z_2' which prevents that S acquires a vacuum expectation value after the EWSB. All the SM fields are even under both symmetries Z_2 and Z_2'. The Lagrangian up to renormalizable level would be

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\left|\partial_\mu S\right|^2 + \mathcal{L}_{\rm V} + \mathcal{L}_{\phi \rm V} + \mathcal{L}_{\rm VS} - V(\phi, S) \tag{1}$$

where the $\mathcal{L}_{\rm SM}$ consider all the known field with the exception of the Higgs potential and $\frac{1}{2}\left|\partial_\mu S\right|^2$ is the kinetical term for the scalar field S. $\mathcal{L}_{\rm V}$ is the vector dark sector given by

$$\begin{aligned} \mathcal{L}_{\rm V} &= -\frac{1}{2}\left(D_\mu V_\nu - D_\nu V_\mu\right)^\dagger \left(D^\mu V^\nu - D^\nu V^\mu\right) + m_V^2 V_\mu^\dagger V^\mu - \alpha_2 (V_\mu^\dagger V^\mu)(V_\nu^\dagger V^\nu) \\ &- \alpha_3 (V_\mu^\dagger V^\nu)(V_\nu^\dagger V^\mu) + i\frac{g'}{2}\kappa_1 V_\mu^\dagger B^{\mu\nu} V_\nu + ig\kappa_2 V_\mu^\dagger W^{\mu\nu} V_\nu \end{aligned} \tag{2}$$

$\mathcal{L}_{\phi \rm V}$ is the interaction sector between the dark vector and the Higgs field

$$\mathcal{L}_{\phi \rm V} = -\lambda_2 (\phi^\dagger\phi)(V_\mu^\dagger V^\mu) - \lambda_3 (\phi^\dagger V_\mu)(V^{\mu\dagger}\phi) - \frac{\lambda_4}{2}\left[(\phi^\dagger V_\mu)(\phi^\dagger V^\mu) + (V^{\mu\dagger}\phi)(V_\mu^\dagger\phi)\right] \tag{3}$$

$\mathcal{L}_{\rm VS}$ is the interaction sector between the dark vector and the dark scalar field

$$\mathcal{L}_{\rm VS} = -\lambda_{SV} S^2 V_\mu^\dagger V^\mu \tag{4}$$

and finally $V(\phi, S)$ is the potential of the model given by

$$V(\phi, S) = -m_\phi^2 \phi^\dagger\phi + \lambda_\phi (\phi^\dagger\phi)^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \lambda_{\phi S}\phi^\dagger\phi S^2 \tag{5}$$

The Lagrangian 1 contain 10 free parameters[1] which we labeled as $\lambda_2, \lambda_3, \lambda_4$ for quartic coupling involving interactions between SM-Higgs field and the dark vector field, λ_S for self interaction quartic coupling of the scalar S, $\lambda_{\phi S}$ and λ_{SV} for quartic coupling involving interactions between SM-Higgs field and the new scalar as well the vector field respectively, two mass terms m_V and m_S, and α_2, α_3 for quartic couplings of pure interactions among the vector fields.

After the electroweak Symmetry Breaking, the tree level mass spectrum of the new sector is

$$\begin{aligned} M_S^2 &= 2m_S^2 - v^2\lambda_{\phi S} && (6) \\ M_{V^\pm}^2 &= \frac{1}{2}\left[2m_V^2 - v^2\lambda_2\right], && (7) \\ M_{V^1}^2 &= \frac{1}{2}\left[2m_V^2 - v^2(\lambda_2+\lambda_3+\lambda_4)\right], && (8) \\ M_{V^2}^2 &= \frac{1}{2}\left[2m_V^2 - v^2(\lambda_2+\lambda_3-\lambda_4)\right], && (9) \end{aligned}$$

The term proportional to λ_4 makes the splitting between the physical masses of the two neutral states. For phenomenological proposes we will work in a different base of free parameters

$$M_{V^1}, \quad M_{V^2}, \quad M_{V^\pm}, \quad M_S, \quad \lambda_L, \quad \lambda_{\phi S}, \quad \lambda_{SV}, \quad \lambda_S, \quad \alpha_1 \quad \alpha_2 \tag{10}$$

[1]We assume that all the free parameters are real, otherwise, the new vector sector may introduce CP-violation sources. In this work we do not deal with that interesting possibility.

where $\lambda_L = \lambda_2 + \lambda_3 + \lambda_4$ is, as we will see, the effective coupling controlling the interaction between the SM Higgs and V^1.

It is convenient to write the quartic coupling and the mass parameters as a function of the new free parameters

$$\lambda_2 = \lambda_L + 2\frac{\left(M_{V^1}^2 - M_{V^\pm}^2\right)}{v^2}, \qquad \lambda_3 = \frac{2M_{V^\pm}^2 - M_{V^1}^2 - M_{V^2}^2}{v^2},$$
$$\lambda_4 = \frac{M_{V^2}^2 - M_{V^1}^2}{v^2}, \qquad m_V^2 = M_{V^1}^2 + \frac{v^2\lambda_L}{2}, \qquad m_S^2 = \frac{M_S^2 + v^2\lambda_{\phi S}}{2}. \tag{11}$$

For future convenience, it will be useful to introduce

$$\lambda_R \equiv \lambda_2 + \lambda_3 - \lambda_4 = \lambda_L + \frac{2\left(M_{V^2}^2 - M_{V^1}^2\right)}{v^2}, \tag{12}$$

which is not a new free parameter, but it is the effective coupling constant which governs the HV^2V^2 interaction.

It is important to mention that because the new vector field have the same quantum numbers than the SM-Higgs field, the two neutral vectors have opposite CP-parities. However we can switch their parity just making a change of bases $V_\mu \to iV_\mu$ and then re-label each field as $V_\mu^1 \to V_\mu^2$ and $V_\mu^2 \to V_\mu^1$ and still obtaining the same phenomenology. Therefore, without loose of generality, we will choose V_μ^1 as the LOP turning it into our Dark Matter candidate. Following the same line, to make sure that V_μ^1 is the lightest state of the new sector, we can find some restrictions that the quartic couplings must follow to satisfy this condition. Considering this we can stress that

$$\begin{aligned} M_{V^2}^2 - M_{V^1}^2 > 0 \qquad &\Rightarrow \;\; \lambda_4 > 0, \\ M_{V^\pm}^2 - M_{V^1}^2 > 0 \qquad &\Rightarrow \;\; \lambda_3 + \lambda_4 > 0. \end{aligned} \tag{13}$$

In order to have a weakly interacting model, we set that all the couplings parameters must to satisfy

$$|\lambda_i| < 4\pi \quad \wedge \quad |\alpha_j| < 4\pi \qquad (i = 2,3,4; \quad j = 2,3). \tag{14}$$

We implemented this model using the `LanHEP`[?] package and we used `CalcHEP`[?] and `micrOMEGAs`[?, ?, ?] for collider and DM phenomenology calculations, respectively.

3 Constraints from LEP, LHC, DM relic density and Direct Detection experiments

4 Dark matter phenomenology

5 Conclusions

Acknowledgements

FR was supported by Conicyt Becas Chile Postdoctorado grant 74180065.

References

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