SCALAR DARK MATTER CANDIDATE IN MULTI-HIGGS MODELS

D. SOKOŁOWSKA

University of Warsaw, Faculty of Physics,
Pasteura 5, 02-093 Warsaw, Poland.

In many scalar Dark Matter (DM) models an imposed discrete symmetry will result in CP conservation. We present an example of a DM candidate from the Three-Higgs Doublet Model (3HDM) which have different CP-symmetry properties, leading to the new regions of DM relic density opened up by CP-violation, and constrain the parameter space of the CP-violating model using recent results from the LHC and DM direct and indirect detection experiments.

1 Introduction

In 2012 a discovery of a scalar boson with a mass of ≈ 125 GeV was reported by both ATLAS and CMS experiments at the CERN Large Hadron Collider (LHC) [1]. Although the properties of the observed boson are in agreement with these of the Higgs boson of the Standard Model (SM), it may just be one member of an extended scalar sector. As of 2017, no signs of detection of physics Beyond SM (BSM) have been reported, but it is well understood that the SM of particle physics is not complete. A good motivation for BSM is the lack of a Dark Matter (DM) candidate in the SM. Various DM candidates exist in the literature, the most well-studied being Weakly Interacting Massive Particles (WIMPs) [2]. Any such WIMP candidate must be cosmologically stable, usually due to the conservation of a discrete symmetry, and must freeze-out to result in the observed relic density of $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ [3].

The SM has no WIMP, however, extending the scalar sector by a doublet, with a zero Vacuum Expectation Value (VEV) and an unbroken discrete Z_2 symmetry, can provide a viable DM candidate [4]. This possibility, known as the Inert Doublet Model (IDM), has been studied extensively for the last few years, and although its parameter space is limited by recent experimental results, it remains a viable DM model [5].

In recent papers [6] we studied DM in a model with 2 inert plus 1 active Higgs doublet (the I(2+1)HDM), where CP symmetry was conserved. Here we discuss chosen scenarios for the CP-violating I(2+1)HDM [7]. We found that presence of complex parameters in the scalar potential changes the annihilation scenarios of the DM candidate, opening new regions of parameter space in agreement with all experimental constraints.

2 The scalar sector of 3HDM

A Z_2 symmetry under which the three scalar doublets $\phi_{1,2,3}$ transform is defined as $g_{Z_2} = \mathrm{diag}\,(-1,-1,1)$. A Z_2-symmetric 3HDM potential[a] is of the following form[8]:

$$\begin{aligned} V_{3HDM} &= -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) - \mu_3^2(\phi_3^\dagger\phi_3) + \lambda_{11}(\phi_1^\dagger\phi_1)^2 + \lambda_{22}(\phi_2^\dagger\phi_2)^2 + \lambda_{33}(\phi_3^\dagger\phi_3)^2 \\ &+\lambda_{12}(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_{23}(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) + \lambda_{31}(\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1) \\ &+\lambda'_{12}(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda'_{23}(\phi_2^\dagger\phi_3)(\phi_3^\dagger\phi_2) + \lambda'_{31}(\phi_3^\dagger\phi_1)(\phi_1^\dagger\phi_3), \\ &-\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c. \end{aligned}$$

where CP violation (CPV) is introduced explicitly through complex parameters of the potential: $\mu_{12}^2, \lambda_{1,2,3}$. Here, we study a simplified version of the I(2+1)HDM where the following equalities were imposed $\mu_1^2 = \mu_2^2, \lambda_3 = \lambda_2, \lambda_{31} = \lambda_{23}, \lambda'_{31} = \lambda'_{23}$. We call it the "dark democracy" limit. Now, there are only two parameters that remain complex[b]: $\mu_{12}^2 = |\mu_{12}^2|e^{i\theta_{12}}$ and $\lambda_2 = |\lambda_2|e^{i\theta_2}$; θ_{12} and θ_2 are the respective CPV phases.

The doublets are defined as

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0+iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0+iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}, \tag{1}$$

where ϕ_1 and ϕ_2 are the two Z_2-odd doublets (hence are inert) and ϕ_3 is the active doublet, which is even under the Z_2 and plays the role of the SM-Higgs doublet. The symmetry of the potential is therefore respected by the vacuum alignment. Once an even Z_2 parity is assigned to all SM particles, identical to the Z_2 parity of the only doublet that couples to them, i.e., the active doublet ϕ_3 [9] (the Yukawa Lagrangian of the model is identical to the SM Yukawa Lagrangian), the entire Lagrangian becomes Z_2-symmetric. The conservation of Z_2-symmetry leads to the lightest particle from $\phi_{1,2}$ to be stable. Among the Z_2-odd particles there are four neutral states, S_i, and two charged states, $S_i^\pm$. Note that the scalar h contained in the doublet ϕ_3 in our model, has exactly the couplings of the SM-Higgs boson. The CPV is only introduced in the *inert* sector which is forbidden from mixing with the *active* sector by the Z_2 symmetry.

The neutral physical states are composed of all neutral base states from (1), so have a mixed CP-charge. We take S_1 to be the lightest neutral field from the inert doublets:

$$\begin{aligned} S_1 &= \frac{\alpha H_1^0 + \alpha H_2^0 - A_1^0 + A_2^0}{\sqrt{2\alpha^2+2}}, \quad & S_2 &= \frac{-H_1^0 - H_2^0 - \alpha A_1^0 + \alpha A_2^0}{\sqrt{2\alpha^2+2}}, \\ S_3 &= \frac{\beta H_1^0 - \beta H_2^0 + A_1^0 + A_2^0}{\sqrt{2\beta^2+2}}, \quad & S_4 &= \frac{-H_1^0 + H_2^0 + \beta A_1^0 + \beta A_2^0}{\sqrt{2\beta^2+2}}, \end{aligned} \tag{2}$$

where α and β are the rotation angles[7].

In the following analysis we take the masses of $S_{1,2}, S_{1,2}^\pm$, the two angles θ_2 and θ_{12} and the Higgs-DM coupling, $g_{S_1S_1h}$, as the input parameters of the model.

In the analysis, various theoretical and experimental constraints are taken into account, including: positivity constraints, S,T,U limits, relic density observations, DM direct and indirect detection, the contribution of the new scalars to the W and Z widths, null searches for charged scalars at LEP and LHC, invisible Higgs decays, Higgs total decay width and the $h\to\gamma\gamma$ signal strength[7].

[a] Following Z_2-respecting terms $(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_3)$, $(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_3)$, $(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1)$ and/or $(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_2)$ can be removed through reparametrization freedom and do not change the phenomenology of the model.

[b] λ_1 governs the self-coupling of inert particles and does not influence DM or LHC phenomenology studied here.

3 DM in the I(2+1)HDM

The I(2+1)HDM studied here has many features of a Higgs-portal DM model. If DM mass is small then the crucial DM annihilation channel is $S_1S_1 \to h \to f\bar{f}$, with the cross-section depending on both m_{DM} and the Higgs-DM coupling. In general, if $m_{DM} < m_h/2$, then a relatively large coupling is needed for a valid $\Omega_{DM}h^2$. Processes with gauge bosons in the final state also contribute to the total annihilation cross section. These contributions are suppressed if $m_{S_1} < m_W$, however it is known that diagrams with off-shell gauge bosons may be important.

If the mass splitting between S_i and the lightest Z_2-odd particle S_1 is comparable to the thermal bath temperature T in the early Universe, coannihilation effects play an important role in scenarios with multiple particles that are close in mass. Processes such as $S_1S_i \to h \to f\bar{f}, S_1S_i \to Z^* \to f\bar{f}, S_1S_j^\pm \to W^{\pm *} \to ff'$ with $i = 2,3,4$ and $j = 1,2$ are included in calculating the effective annihilation cross section. If all inert particles are very close in mass then all channels $S_iS_j \to h \to f\bar{f}, S_iS_j \to VV$ contribute to the final DM relic density.

In the CP-conserving version of the I(2+1)HDM (within the "dark democracy" limit) [6], couplings between inert scalars and gauge bosons are fixed, and given by the rotation angles $\theta_a = \theta_h = \pi/4$. They do not depend on the mass splittings or the value of m_{S_1}. In the CP-violating case the situation is different, as the strength of gauge-inert interaction depends on parameters α and β, which in turn depend on m_{S_i}. Higgs-inert scalar couplings are also modified with respect to the CP-conserving case [7]. This leads to important differences in DM phenomenology, especially in the region where coannihilation channels are important.

Below we discuss three scenarios for low and medium DM mass. In *Scenario A*, where there are large mass splittings between S_1 and all other inert particles ($m_{S_1} \ll m_{S_2}, m_{S_3}, m_{S_4}, m_{S_1^\pm}, m_{S_2^\pm}$), no coannihilation channels are present. In *Scenario B*, where $m_{S_1} \sim m_{S_3} \ll m_{S_2}, m_{S_4}, m_{S_1^\pm}, m_{S_2^\pm}$, S_1 can coannihilate only with S_3. In *Scenario C*, where $m_{S_1} \sim m_{S_3} \sim m_{S_2} \sim m_{S_4} \ll m_{S_1^\pm}, m_{S_2^\pm}$, all other neutral inert particles can coannihilate.

Low DM mass region: $\mathbf{m_{S_1} < m_h/2}$ In scenario A, there are no coannihilation channels and S_1 annihilates mostly through $S_1S_1 \to h \to b\bar{b}$, entering the resonance region with small Higgs-DM coupling for masses close to $m_h/2$. This benchmark resembles both the CP-conserving I(2+1)HDM as well as the IDM. For scenario B the coannihilation channel $S_1S_3 \to Z \to f\bar{f}$ is open. In the absence of CP-violation this leas to a $\Omega_{DM}h^2$ that is too small. With CP-violation there is an additional freedom to tune $g_{S_1S_1h}$, which can cure this issue. In scenario C all coannihilation diagrams could be important. The couplings $g_{S_1S_2h}, g_{S_3S_4h}$ and $g_{ZS_1S_3}$ are suppressed, and the crucial contribution comes from $S_1S_4 \to Z \to q\bar{q}$. In the CP-conserving case, this scenario is only viable in the resonance region, but in the CP-violating case the strength of the coannihilation channels depends on the input parameters and can therefore vary.

Medium DM mass region: $\mathbf{m_h/2 < m_{S_1} < m_{W^\pm,Z}}$ The crucial channel for all benchmarks is the annihilation of $S_1S_1 \to W^+W^-$ and this vertex does not depend on parameters α and β, but only the DM mass. This is why all studied scenarios, as well as the CP-conserving scenarios, follow the similar behaviour, known from the IDM [7]. Coannihilation channels, like $S_1S_4 \to q\bar{q}$ or $S_3S_3 \to W^+W^-$ give small contributions, leading to small deviations from the behaviour of scenario A.

Experimental constraints DM direct detection experiments aim to measure the scattering of DM particle off nuclei. This interaction is mediated by the Higgs particle, and therefore results of these experiments constrain m_{DM}, and its coupling to h. In the low and medium mass region the strongest constraints come from the LUX experiment [10]. We found that as long as $g_{S_1S_1h}$ is small, is possible to obtain good solutions for $40\,\text{GeV} \lesssim m_{S_1} \lesssim 76\,\text{GeV}$ [7].

Recent indirect detection results from Fermi-LAT strongly constrain the DM candidate annihilating into $b\bar{b}$ pair [11]. The CP-conserving scalar Higgs-portal type of DM with proper $\Omega_{DM}h^2$ and $m_{S_1} \lesssim 53$ GeV is ruled out. The same limit applies to scenario A, as the dominant annihilation channel is into $b\bar{b}$ pair. For cases B and C annihilation channels are different and a good relic density is obtained for smaller values of Higgs-DM coupling. This weakens the annihilation into $b\bar{b}$, leading to most of the parameter space to lie within the allowed region [7].

The presence of additional light scalars can modify decays of the Higgs particle. Channel $h \to S_1 S_1$ contributes to the Higgs invisible decay ratio (BR($h \to$ inv.)). All other inert particles can contribute to the total decay width of h. These two limits, combined with measurements of $h \to \gamma\gamma$ signal strength [12], constrain heavily parameter space, pointing towards $g_{S_1 S_1 h} \to 0$ in the low DM mass region. In case of scenario B, LHC constraints are actually stronger than DM detection experiments, excluding masses below 53 GeV if $m_{S_1} \sim m_{S_3}$ [7]. It is especially important considering the astrophysical uncertainties that may influence interpretation of results provided by DM detection experiments.

4 Conclusion

The extended scalar sector of the 3HDM, and the inclusion of complex parameters in the scalar potential, accommodates both the DM candidate and an unbounded amount of possible CPV. We find that with the introduction of CP violation, the strength of the gauge-inert couplings which were fixed in the CP conserving limit, become unconstrained, allowing us for more freedom and giving the access to a previously excluded part of parameter space. In particular, it is possible to have a light DM candidate, with very small DM-Higgs coupling, that is in agreement with all experimental data, unlike in the IDM or CP-conserving I(2+1)HDM.

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References

1. G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1; S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30.
2. G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267** (1996) 195; G. Bertone, D. Hooper and J. Silk, Phys. Rept. **405** (2005) 279; L. Bergström, Rept. Prog. Phys. **63** (2000) 793
3. P. A. R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. **594** (2016) A13
4. N. G. Deshpande and E. Ma, Phys. Rev. D **18** (1978) 2574.
5. E. Ma, Phys. Rev. D **73** (2006) 077301; R. Barbieri, L. J. Hall and V. S. Rychkov, Phys. Rev. D **74** (2006) 015007; L. Lopez Honorez, E. Nezri, J. F. Oliver and M. H. G. Tytgat, JCAP **0702** (2007) 028; M. Krawczyk, D. Sokolowska, P. Swaczyna and B. Swiezewska, JHEP **1309** (2013) 055; A. Arhrib, Y. L. S. Tsai, Q. Yuan and T. C. Yuan, JCAP **1406** (2014) 030; A. Ilnicka, M. Krawczyk and T. Robens, Phys. Rev. D **93** (2016) no.5, 055026
6. V. Keus, S. F. King, S. Moretti and D. Sokolowska, JHEP **1411** (2014) 016 V. Keus, S. F. King, S. Moretti and D. Sokolowska, JHEP **1511** (2015) 003
7. A. Cordero-Cid, J. Hernndez-Snchez, V. Keus, S. F. King, S. Moretti, D. Rojas and D. Sokołowska, JHEP **1612** (2016) 014
8. I. P. Ivanov, V. Keus and E. Vdovin, J. Phys. A **45** (2012) 215201
9. I. P. Ivanov and V. Keus, Phys. Rev. D **86** (2012) 016004
10. D. S. Akerib *et al.* [LUX Collaboration], Phys. Rev. Lett. **118** (2017) no.2, 021303
11. M. Ackermann *et al.* [Fermi-LAT Collaboration], Phys. Rev. Lett. **115** (2015) no.23, 231301
12. G. Aad *et al.* [ATLAS Collaboration], JHEP **1511** (2015) 206; CMS Collaboration [CMS Collaboration], CMS-PAS-HIG-15-012; K. A. Olive *et al.* [Particle Data Group], Chin. Phys. C **38** (2014) 090001.