Journal of Physics G: Nuclear and Particle Physics

PAPER

Scalar dark matter candidates in a two inert Higgs doublet model

To cite this article: E C F S Fortes *et al* 2015 *J. Phys. G: Nucl. Part. Phys.* **42** 105003

IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **42** (2015) 105003 (11pp) doi:10.1088/0954-3899/42/10/105003

Scalar dark matter candidates in a two inert Higgs doublet model

E C F S Fortes, A C B Machado[1], J Montaño and V Pleitez

Instituto de Física Teórica–Universidade Estadual Paulista R. Dr. Bento Teobaldo Ferraz 271, Barra Funda São Paulo-SP, 01140–070, Brazil

E-mail: elaine@ift.unesp.br, ana@ift.unesp.br, montano@ift.unesp.br and vicente@ift.unesp.br

Received 24 February 2015, revised 21 July 2015
Accepted for publication 5 August 2015
Published 9 September 2015

CrossMark

Abstract

We study a two scalar inert doublet model (IDMS$_3$) which is stabilized by an S_3 symmetry considering two scenarios: (a) two of the scalars in each charged sector are mass degenerated due to a residual $\mathbb{Z}_2$ symmetry, (b) there is no mass degeneracy because of the introduction of soft terms that break the $\mathbb{Z}_2$ symmetry. A major difference between this model and the one with only one inert Higgs doublet (IDM) is that it has twice the number of possible dark matter (DM) candidates. In particular we show that for the case (a) it is possible to have two CP even DM candidates. Besides, in case (b) the upper limit to the intermediate mass region for the one IDM in our model is larger, once we obtain a DM candidate with mass equals to 257 GeV.

Keywords: dark matter, inert doublets, multi Higgs model

(Some figures may appear in colour only in the online journal)

1. Introduction

The existence of dark matter (DM) has been well established since the early astronomical [1] and cosmological observations [2–5]. For more recent data see [6]. It accounts for approximatively 23% of the composition of the Universe. Moreover, these observational evidence justify the experimental searches trying to find events that can be interpreted as direct manifestations of DM. Some of them are astronomical observations [7–11], and others like DAMA [12], CoGeNT [13], CDMS [14], XENON [15, 16], and LUX [17] are experiments trying to measure the recoil energy of nuclei if it scatters with the DM.

[1] Author to whom all correspondence should be addressed.

Models which contain DM candidates have to explain among other aspects, the DM density, which is $\Omega h^2 = \rho h^2/\rho_c = 0.1196 \pm 0.0031$ where h is the scale factor for Hubble expansion [18], $\rho_c = 3H_0^2/(8\pi G)$ is the critical density of the Universe, and H_0 is the current value of the Hubble constant [6].

Much effort has been employed in order to discover or interpret DM signals. It is possible that it consists of one or more elementary particles which interact very weakly with ordinary matter. One of the most common scenarios are supersymmetric models [19]. In fact, in this kind of model, the lightest supersymmetric particle (neutralino) is prevented of interacting by the R parity with the known particles. The neutralino is an example of cold dark matter (CDM), i.e. a kind of DM which is not relativistic at the time of freeze out. Of course, there are other possibilities, for instance, Kaluza–Klein states in models with universal [20, 21] or warped [22] extra dimensions, stable states in little Higgs theories [23] and a number of models with extra heavy neutrinos. Some other alternative scenarios for DM consider self-interacting DM [24] and warm DM [25]. Other ambitious scenarios consider asymmetric DM models. They have their motivation based on the similarity of mass densities of the DM (ρ_{DM}) and that of the visible matter (ρ_B) observed $\rho_{\mathrm{DM}}/\rho_B \approx 5$ and try to explain this rate. Consequently, most of these models are based on the hypothesis that the present abundance of DM and visible matter have the same origin [26, 27].

An additional and interesting scenario which contains DM candidates is the inert doublet model (IDM) [28–32]. It is a minimal extension of the standard model (SM) which contains a second Higgs doublet (H_2) with no direct couplings to quarks and leptons and not contribute to the spontaneous symmetry braken. The first time that the phenomenology of an inert doublet was considered was in the context of neutrino physics [33] and also in the context of the problem of naturalness [34]. In all cases, the inert doublet was possible due to a $\mathbb{Z}_2$ symmetry under which $H_2 \to -H_2$ and all the other fields are even. In particular, this discrete symmetry forbids interactions like $(H_1^\dagger H_2)(H_2^\dagger H_2)$, being H_1 the SM Higgs doublet, and prohibits fully the interactions with fermions.

Nowadays astronomical observations suggest that the DM spectrum may be composed of several particles [35–37]. In this work, we study the three Higgs doublet model with an S_3 symmetry, proposed in [38] in which, besides the SM like doublet there are two additional inert doublets here denoted by H_2 and H_3. It is this S_3 symmetry and an appropriate vacuum alignment that allows us to obtain a model with two inert doublets. Although this model can accommodate four DM candidates, it is out of the scope of this paper to realize a complete study of all the possibilities for the DM scenarios. We will only analyze only two scenarios which already show the difference from the IDM model: scenario 1 in which the extra scalars are mass degenerated and the other, scenario 2, in which soft terms breaking a residual $\mathbb{Z}_2$ symmetry, are added, resulting in non degenerated masses for this extra scalars. In scenario 1, we have two CP even DM components, each one corresponding to 50% of the DM relic density. Moreover, in scenario 2 we obtain a solution for the DM candidate with a mass which is out the intermediate region obtained for the IDM.

The paper is organized as follows. In section 2 we briefly present the model. In section 3 we briefly describe the theoretical framework for the calculations for DM abundance and in the section 4 we show the parameter choices suitable for the DM candidate and the numerical results. Finally in the last section section, section 5, we summarize our conclusions.

2. The model

In the context of the SM the number of scalar doublets can be arbitrary. An interesting case occurs when the number of these fields is the same as the number of the fermion families, i.e. just three. In this case the S_3 symmetry is, probably, the most interesting one because it is the minimal non-abelian discrete symmetry with one doublet and one singlet irreducible representations.

The model that we will consider here has the three Higgs doublets transforming as $(2, +1)$ under $SU(2)_L \otimes U(1)_Y$ and under S_3 as

$$\begin{aligned} &S = H_1 \sim 1, \\ &D = (D_1, D_2) \cong (H_2, H_3) \sim 2. \end{aligned} \tag{1}$$

The necessary conditions under which the vacuum alignment $v_1 = v_{\rm SM}$ ($v_{\rm SM}$ is the SM VEV $\sim$246 GeV) and $v_2 = v_3 = 0$, allow a scalar potential bounded from below and a stable minimum as has been shown in [38]. With this vacuum alignment and, since the quarks and leptons are singlet of S_3, the two Higgs doublet D_1, D_2 do not couple to fermions and do not contribute to the spontaneous symmetry breakdown, i.e they are inert. They couple only to the gauge bosons and this vacuum alignment also implies in a residual $\mathbb{Z}_2$ symmetry in which the two inert doublets are mass degenerate in each charged sector. In this case the mass spectra is

$$\begin{aligned} &m_h^2 = \lambda_4 v_{\rm SM}^2, \quad m_{H_2^0}^2 = m_{H_3^0}^2 = \mu_d^2 + \frac{1}{2}\lambda' v_{\rm SM}^2, \\ &m_{A_2}^2 = m_{A_3}^2 = \mu_d^2 + \frac{1}{2}\lambda'' v_{\rm SM}^2, \\ &m_{h_2^+}^2 = m_{h_3^+}^2 = \frac{1}{4}\left(2\mu_d^2 + \lambda_5 v_{\rm SM}^2\right), \end{aligned} \tag{2}$$

where m_h^2 is the SM-like Higgs boson (here denoted by h), $\mu_d^2 > 0$ came from the term $\mu_d^2 [D^\dagger D]_1$ in the scalar potential, where $\lambda' = \lambda_5 + \lambda_6 + 2\lambda_7$ and $\lambda'' = \lambda_5 + \lambda_6 - 2\lambda_7$, with $\lambda_{4,5,6,7}$ are quartic coupling constants in the scalar potential. We call this scenario 1.

If the residual $\mathbb{Z}_2$ symmetry is softly broken by adding non-diagonal quadratic terms in the inert sector, the mass degeneracy is broken and the mass spectra becomes

$$\begin{aligned} &\overline{m}_{H_2^0}^2 = m_{H_2^0}^2 - \nu^2, \quad \overline{m}_{H_3^0}^2 = m_{H_3^0}^2 + \nu^2, \\ &\overline{m}_{A_2}^2 = m_{A_2}^2 - \nu^2, \quad \overline{m}_{A_3}^2 = m_{A_3}^2 + \nu^2, \\ &\overline{m}_{h_2^+}^2 = m_{h_2^+}^2 - \nu^2, \quad \overline{m}_{h_2^+}^2 = m_{h_2^+}^2 + \nu^2, \end{aligned} \tag{3}$$

and we call this scenario 2.

In the case of mass degenerate scalars, the lightest scalars can be DM candidates and we will choose the CP even ones. In the case of no mass degeneracy it is possible that the lightest one is the DM candidate or we can have up to four DM components. For the scenario 1, our parameter choice enables us to establish the follow order for the mass of the scalars: $m_{A_{2,3}} > m_{h_{2,3}^+} > m_{H_{2,3}^0}$. Since $H_{2,3}^0$ are the lightest neutral scalars, their decays are kinematically forbidden. With the rearrangement of the parameters, instead of choosing $H_{2,3}^0$, we could choose the CP odd scalars $A_{2,3}$ as the DM candidates, if they were the lightest ones, and the same conclusions would remain valid for this scenario. In scenario 2, H_2^0 accounts for all the $\Omega_{\rm DM} h^2$ contribution. For each scenario, with the couplings shown in table 1, we choose two set of parameters for scenario 1 and five sets of parameters for scenario 2, as is shown in table 2.

Table 1. Interactions and the corresponding couplings

Interaction	Coupling
$H_2^0 H_2^0\, h,\ H_3^0 H_3^0\, h$	$\lambda' v_{\mathrm{SM}}$
$H_2^0 H_2^0\, hh,\ H_3^0 H_3^0\, hh$	λ'
$H_2^0 H_2^0 W^+ W^-,\ H_3^0 H_3^0 W^+ W^-$	$\frac{g^2}{2}$
$H_2^0 H_2^0 ZZ,\ H_3^0 H_3^0 ZZ$	$\frac{g^2}{2}\cos^2_{\theta_W}(1+\tan_{\theta_W})^2$
$H_2^0 H_2^0 h_2^+ h_2^-,\ H_2^0 H_2^0 h_3^+ h_3^-$	$-(\lambda_1+\lambda_3)$
$H_3^0 H_3^0 h_2^+ h_2^-,\ H_3^0 H_3^0 h_3^+ h_3^-$	$-(\lambda_1+\lambda_3)$
$H_2^0 H_2^+ h_2^-$	0
$H_2^0 H_3^+ h_3^-$	0
$H_2^0 A_2^0 Z,\ H_3^0 A_3^0 Z$	$-g\cos_{\theta_W}\frac{1+\tan_{\theta_W}}{2}$
$H_2^0 h_2^+ W^-$	$\mathrm{i}\frac{g}{\sqrt{2}}$
$H_3^0 h_3^+ W^-$	$\mathrm{i}\frac{g}{\sqrt{2}}$

3. DM abundance

Preliminary analysis showing that this model can accommodate at least one DM candidate was done in [38]. Here, this will be confirmed by a more detailed analysis. In order to calculate the DM abundance we have used the MicrOMEGAs package to solve numerically the Boltzmann equation after implementing all the interactions of the model in the CalcHEP package [39]. The Feynman diagrams for the annihilations process for this model are given in figure 1.

Let us consider for instance, the model of inert doublets with non degenerated mass (scenario 2). In this case, as we already said in section 2, H_2^0 is our DM candidate. The evolution of the numerical density n of H_2^0, at the temperature T in the early Universe, is given by the Boltzmann equation, which is written in simplified form as follows [40]:

$$\frac{\mathrm{d}Y}{\mathrm{d}y} = -\sqrt{\frac{\pi g_*}{45G}}\frac{m_{H_2^0}}{y^2}\left\langle \sigma_{\mathrm{ann}} |v| \right\rangle \left(Y^2 - Y_{\mathrm{eq}}^2\right), \tag{4}$$

here $Y = n/s$, s is the entropy per unity of volume, Y_{eq} is the Y value in the thermal equilibrium, $y = m_{H_2^0}/T$. The parameter G in equation (4) is the Newton gravitational constant, σ_{ann} is the cross section for annihilation of the particle H_2^0 and v is the relative velocity, and the symbol $\langle\rangle$ represents thermal average. Finally, g_* is a parameter that measures the effective number of degrees of freedom at freeze-out, which is expressed as

$$g_* = \sum_{i=\mathrm{bosons}} g_i\left(\frac{T_i}{T}\right)^4 + \frac{7}{8}\sum_{i=\mathrm{fermions}} g_i\left(\frac{T_i}{T}\right)^4, \tag{5}$$

Table 2. Parameters choice for scenario 1 and 2 with $m_h = 125$ GeV. The other masses units are in GeV, σv is in units of 10^{-26} $\mathrm{cm}^3\,\mathrm{s}^{-1}$ and the units for σ^{SI} are in cm^2. The parameters $\lambda'' = 0.34$ and $\lambda_5 = 0.4$ for scenarios 1a,1b, 2a, 2b, $\lambda_5 = -0.3$ for scenario 2c, $\lambda_5 = 0.2$ for 2d, finally for 2e we used $\lambda_5 = 1.3$ and $\lambda'' = 0.2$.

Parameter	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 2c	Scenario 2d	Scenario 2e
$m_{H_2^0}$	54.12	79.77	63.46	59.01	161.80	130.20	256.7
$m_{H_3^0}$	54.12	79.77	76.20	72.52	167.21	142.94	263.67
$m_{A_2^0}$	112.44	127.98	117.19	117.22	190.89	163.30	263.64
$m_{A_3^0}$	112.44	127.98	131.22	131.22	199.79	173.62	270.47
$m_{h_2^+}$	85.02	95.38	83.11	83.12	87.56	101.71	224.69
$m_{h_3^+}$	85.02	95.38	101.91	101.91	105.56	117.57	232.66
μ_d	48.52	78.05	72.05	72.05	167	134.6	255.5
ν	–	–	41.7	41.7	41.7	41.7	42.7
λ'	0.019	0.009	0.019	0.001	0.001	0.019	0.08
Ω	0.12	0.12	0.118	0.119	0.12	0.11	0.11
σv	0.0831	0.003	5	0.0012	0.99	0.841	0.317
$\sigma^{\mathrm{SI}}_{\mathrm{proton}}$	7.33×10^{-46}	7.46×10^{-47}	5.30×10^{-46}	1.7×10^{-48}	2.18×10^{-49}	1.23×10^{-46}	5.28×10^{-46}
$\sigma^{\mathrm{SI}}_{\mathrm{neutron}}$	8.38×10^{-46}	8.55×10^{-47}	6.06×10^{-46}	1.9×10^{-48}	2.50×10^{-49}	1.41×10^{-46}	6.07×10^{-46}

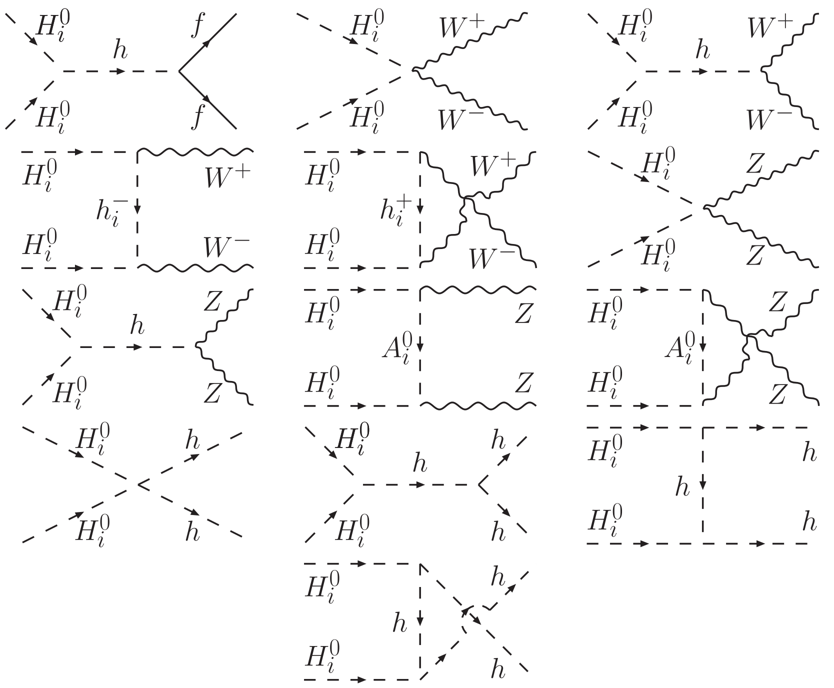

Figure 1. Feynman diagrams for lowest order of two H_i which annihilate into a pair of fermions and anti-fermions, W^+W^-, ZZ and Higgs.

where the sums runs over only those species with mass $m_{H_2^0} \ll T$ [41]. The model studied here has, besides the SM particles, eight extra scalars (A_2^0, A_3^0, H_2^0, H_3^0, $h_2^\pm$, $h_3^\pm$). So, considering, for instance $T \gtrsim 300$ GeV we obtain $g_* \approx 114.75$.

To find Y_0, the present value of Y, equation (4) must be integrated between $y = 0$ and $y_0 = m_{H_2^0}/T_0$. Once this value is found, the contribution of H_2^0 to DM density is

$$\Omega_{h_2} = \frac{m_{H_2^0} s_0 Y_0}{\rho_c}. \tag{6}$$

The same calculations hold for the scenario 1, however in this scenario we consider that the DM has 50% of each component (H_2^0, H_3^0).

4. Results and comments

The main numerical results for this model using the parameters presented in table 2. For more detail about the interactions of the model see [42]. For both scenarios (1 and 2), we have considered some set of parameters, so we call these scenarios respectively scenario 1a, 1b and scenario 2a, 2b, 2c, 2d and 2e.

For scenario 1a, the dominant annihilation channels are: 39% relative to $H_3^0 H_3^0 \to b\bar{b}$, 39% to $H_2^0 H_2^0 \to b\bar{b}$, 5% to $H_3^0 H_3^0 \to GG$, 5% to $H_2^0 H_2^0 \to GG$, 4% to $H_3^0 H_3^0 \to \tau^+\tau^-$, 4% to $H_2^0 H_2^0 \to \tau^+\tau^-$, 2% to $H_3^0 H_3^0 \to c\bar{c}$ and 2% due to $H_2^0 H_2^0 \to c\bar{c}$. The contributions of the two candidates (H_3^0, H_2^0) to the Higgs invisible decay is 34.8%. The Higgs invisible decay depends strongly on the parameter λ'. In scenario 1, another choice of parameters which

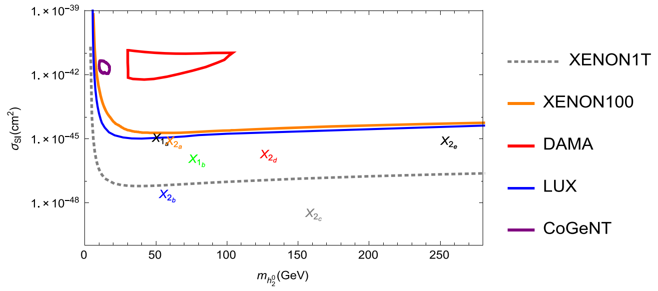

Figure 2. Limits for $\sigma_{\rm SI}$ according to the experiments CoGent, DAMA, XENON100, XENON1T and LUX. The points $X_{1\rm a}$, $X_{1\rm b}$, $X_{2\rm a}$, $X_{2\rm b}$, $X_{2\rm c}$, $X_{2\rm d}$ and $X_{2\rm e}$ are the ones which refer to scenarios 1a, 1b, 2a, 2b, 2c, 2d and 2e given in Table 2.

brings null contributions to this invisible decay is reached with the numbers presented in scenario 1b. The dominant annihilation channels are in this case 50% relative to $H_3^0 H_3^0 \to W^+W^-$ and 50% relative to $H_2^0 H_2^0 \to W^+W^-$.

Next we consider scenario 2, in which H_2^0 is the DM candidate. In scenario 2a, the dominant annihilation channels are respectively 77% relative to $H_2^0 H_2^0 \to b\bar{b}$, 11% to $H_2^0 H_2^0 \to GG$, 8% to $H_2^0 H_2^0 \to \tau^+\tau^-$ and 3% due to $H_2^0 H_2^0 \to c\bar{c}$. In this scenario, H_2^0 does not contribute to the Higgs invisible decay. In scenario 2b, the dominant annihilation channels are 78% relative to $H_2^0 H_2^0 \to b\bar{b}$, 10% relative to $H_2^0 H_2^0 \to GG$, 8% relative to $H_2^0 H_2^0 \to \tau^+\tau^-$ and 3% relative to $H_2^0 H_2^0 \to c\bar{c}$. In scenario 2c, the dominant annihilation channel is 100% due to $H_2^0 H_2^0 \to W^+W^-$. In scenario 2d, the dominant annihilation channels are respectively 97% relative to W^+W^- and 3% relative to hh, finally, in scenario 2e, the dominant annihilation channels are 81% em a_2, a_2, 13% em $t\bar{t}$ e 6% em W^+W^-.

For all the scenarios discussed above, the cold DM-nucleons amplitudes are in agreement with CoGent, DAMA, LUX, XENON100. The scenario 2b and 2c are in agreement with the predictions of XENON1T for $\sigma^{\rm SI}$. In this scenario, a negative λ_5 favors mainly the Higgs decay into two neutral gauge bosons [42]. Due to the smallness of $\lambda' = 0.001$, in scenario 2b the branching $h \to H_2^0 H_2^0$ is negligible ($\approx 5 \times 10^{-4}$), since this Higgs decay is very sensible to this parameter.

Figure 2 shows the data presented in table 2 compared to the experimental results for $\sigma^{\rm SI}$ considered in the experiments CoGent, DAMA, LUX, XENON100 and XENON1T.

In order to adjust the DM solutions it is necessary to fix some parameters. Once λ', λ'' and λ_5 are already set, we can determine the values for λ_6 and λ_7 using the relations: $\lambda' = \lambda_5 + \lambda_6 + 2\lambda_7$ and $\lambda'' = \lambda_5 + \lambda_6 - 2\lambda_7$. The numerical results for each scenario are given in table 3.

The figure 3 shows the allowed region for the scalar potential couplings λ_1 and λ_3. In order to obtain this region we have considered the relations between the scalar potential coupling constants, which ensures that the scalar potential is bounded from below, for more detail see [38], namely:

$$\begin{aligned} &\lambda_1 + \lambda_3 \geqslant 0, \\ &\lambda_5 + \sqrt{\lambda_4(\lambda_1 + \lambda_3)} \geqslant 0, \\ &\lambda'' + \sqrt{\lambda_4(\lambda_1 + \lambda_3)} \geqslant 0. \end{aligned} \tag{7}$$

Table 3. Used parameters of table 2 considering $\lambda_6 = \lambda' + \lambda'' - 2\lambda_5$ and $4\lambda_7 = \lambda' - \lambda''$.

Parameter	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 2c	Scenario 2d	Scenario 2e
λ_6	−0.223	−0.223	−0.223	0.471	0.041	−0.02	−1.16
λ_7	−0.080	−0.083	−0.083	−0.085	−0.085	−0.080	−0.03

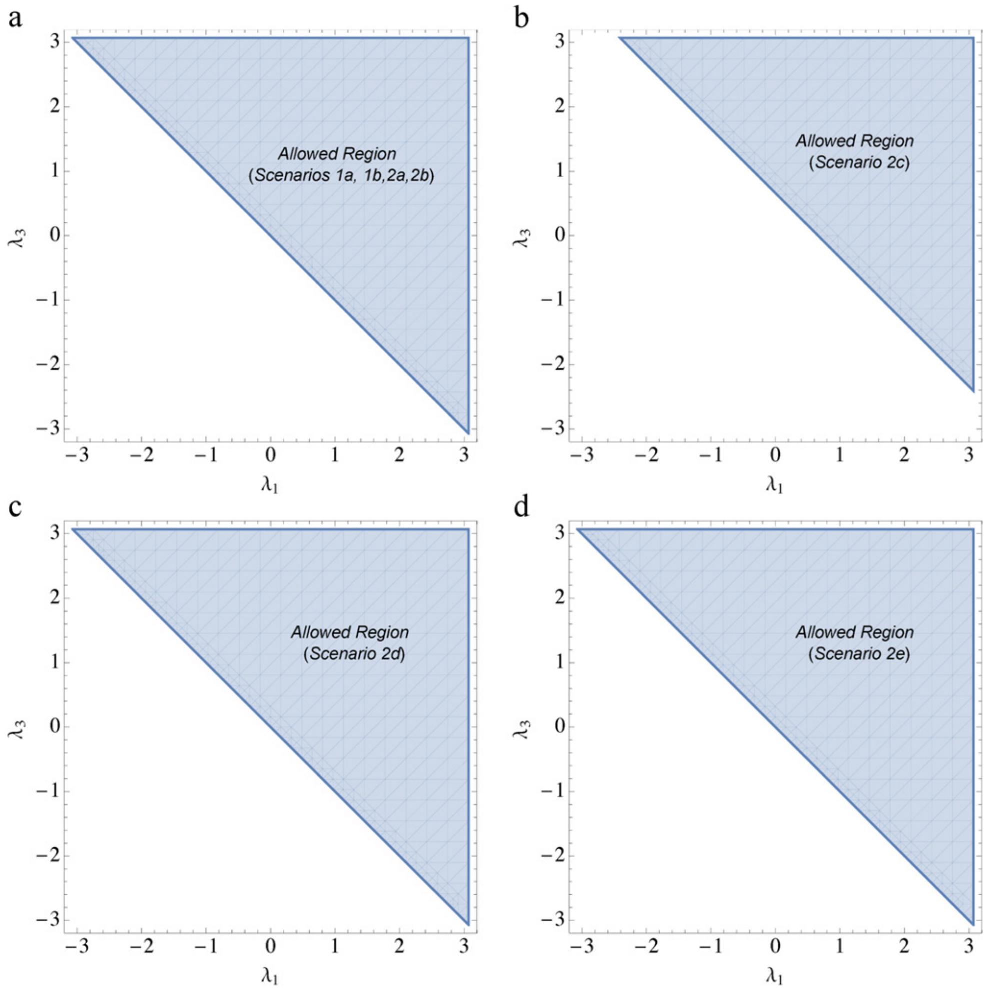

Figure 3. Using equation (7) and the values in table 2 we obtain the allowed region for the scalar potencial couplings λ_1 and λ_3. In (a) for scenarios 1a, 1b, 2a and 2b. In (b) for scenarios 2c, in (c) for 2d and in (d) for 2e.

We have considered the parameter choice of table 2 and the above restrictions. The allowed regions are given in figure 3(a) for scenarios 1a, 1b, 2a and 2b, and in figure 3(b) for scenario 2c. The remaining free parameters now are λ_2 and λ_8. We should mention that λ_2 is the quartic term coupling in interactions between inert scalars.

5. Conclusion

Here we have considered a two IDM with an S_3 symmetry. The model has, besides the SM particles, eight scalars bosons which are inert, i.e. they do not contribute to the spontaneous electroweak symmetry breaking. They interact only among themselves and with the gauge bosons through trilinear and quartic interactions, here only the latter one is important. We have considered here the simplest cases. On one hand, in the case of degenerated masses (scenario 1), the two real neutral scalars play the role of DM candidates each one with a 50% contribution to the relic density. On the other hand, in the case of non-degenerated masses (scenario 2), one of the neutral scalars is the DM candidate. It is well known that in the IDM there are three allowed regions of masses that are compatible with observed value of $\Omega_{\mathrm{DM}}h^2$: (i) 1 GeV $\lesssim m_{H^0} \lesssim$ 10 GeV; (ii) 40–160 GeV, and (iii) 500 GeV $\lesssim m_{H^0} \lesssim$ 10 TeV [43, 44]. However, we have obtain a solution with mass equal to 257 GeV, see point 2e in figure 2.

Moreover, from table 2 and figure 2 we can see that the spin-independent elastic cross section, σ^{SI}, is in good agreement with the results of experiments LUX and XENON100 for the mass range of DM considered here. We have presented scenarios (2b and 2c) where the predictions of XENON1T, to be measured in the future, are matched.

Finally we note that our so-obtained parameters can indeed modify the Higgs boson measurements, for that reason we have performed a complete study of the consequences of such parameters on the Higgs physics in [42]. We have found that our parameter space could give deviations to those one-loop Higss decays; in particular we were able to predict $h \to \gamma Z$ from the effects of our parameters on the channel $h \to \gamma\gamma$, being the signal entirely compatible within the LHC data.

Acknowledgments

ACBM thanks CAPES for financial support. ECFSF and JM thanks to FAPESP for financial support under the respective processes numbers 2011/21945–8 and 2013/09173–5. VP thanks CNPq for partial support. One of us (ECFSF) would like to thank A Pukhov for helpful discussions.

References

[1] Rubin V C and Ford W K Jr 1970 *Astrophys. J.* **159** 379
[2] Riess A G *et al* 1999 *Astron. J.* **117** 707
[3] Perlmutter S *et al* (Supernova Cosmology Project Collaboration) 1999 *Astrophys. J.* **517** 565
[4] Bahcall N A, Ostriker J P, Perlmutter S and Steinhardt P J 1999 *Science* **284** 1481
[5] Larson D *et al* 2011 *Astrophys. J. Suppl.* **192** 16
[6] Olive K A *et al* (Particle Data Group Collaboration) 2014 *Chin. Phys.* C **38** 090001
[7] Cline D 2014 (arXiv:1406.5200)
[8] Hooper D and Linden T 2011 *Phys. Rev.* D **84** 123005
[9] Hooper D and Goodenough L 2011 *Phys. Lett.* B **697** 412
[10] Linden T, Hooper D and Yusef-Zadeh F 2011 *Astrophys. J.* **741** 95
[11] Hooper D, Finkbeiner D P and Dobler G 2007 *Phys. Rev.* D **76** 083012
[12] Bernabei R *et al* (DAMA and LIBRA Collaborations) 2010 *Eur. Phys. J. C* **67** 39
[13] Aalseth C E *et al* (CoGeNT Collaboration) 2011 *Phys. Rev. Lett.* **106** 131301
[14] Ahmed Z *et al* (CDMS-II Collaboration) 2011 *Phys. Rev. Lett.* **106** 131302
[15] Angle J *et al* (XENON10 Collaboration) 2011 *Phys. Rev. Lett.* **107** 051301
[16] Aprile E *et al* (XENON100 Collaboration) 2011 *Phys. Rev. Lett.* **107** 131302
[17] Akerib D S *et al* (LUX Collaboration) 2014 *Phys. Rev. Lett.* **112** 091303
[18] Ade P A R *et al* (Planck Collaboration) 2014 *Astron. Astrophys.* **571** A16
[19] Bertone G, Hooper D and Silk J 2005 *Phys. Rep* **405** 279
[20] Kolb E W and Slansky R 1984 *Phys. Lett.* B **135** 378
[21] Servant G and Tait T M P 2003 *Nucl. Phys.* B **650** 391
[22] Agashe K and Servant G 2004 *Phys. Rev. Lett.* **93** 231805
[23] Birkedal A, Noble A, Perelstein M and Spray A 2006 *Phys. Rev.* D **74** 035002
[24] Fortes E C F S and Tonasse M D 2014 *Phys. Rev.* D **89** 016015
[25] Zavala J, Vogelsberger M and Walker M G 2013 *Mon. Not. R. Astron. Soc.: Lett.* **431** L20
[26] Zurek K M 2014 *Phys. Rep.* **537** 91

[27] Petraki K and Volkas R R 2013 *Int. J. Mod. Phys.* A **28** 1330028
[28] Lopez Honorez L, Nezri E, Oliver J F and Tytgat M H G 2007 *J. Cosmol. Astropart. Phys.* JCAP02(2007)028
[29] Hambye T, Ling F-S, Lopez Honorez L and Rocher J 2009 *J. High Energy Phys.* JHEP07(2009) 090
Hambye T, Ling F-S, Lopez Honorez L and Rocher J 2010 *J. High Energy Phys.* JHEP05(2010) 066 (erratum)
[30] Lopez Honorez L and Yaguna C E 2011 *J. Cosmol. Astropart. Phys.* JCAP01(2011)002
[31] Lopez Honorez L and Yaguna C E 2010 *J. High Energy Phys.* JHEP09(2010)046
[32] Gustafsson M, Rydbeck S, Lopez-Honorez L and Lundstrom E 2012 *Phys. Rev.* D **86** 075019
[33] Ma E 2006 *Phys. Rev.* D **73** 077301
[34] Barbieri R, Hall L J and Rychkov V S 2006 *Phys. Rev.* D **74** 015007
[35] Daikoku Y, Okada H and Toma T 2011 *Prog. Theor. Phys.* **126** 855
[36] Biswas A, Majumdar D, Sil A and Bhattacharjee P 2013 *J. Cosmol. Astropart. Phys.* JCAP12 (2013)049
[37] Bhattacharya S, Drozd A, Grzadkowski B and Wudka J 2013 *J. High Energy Phys.* JHEP10 (2013)158
[38] Machado A C B and Pleitez V 2012 arXiv:1205.0995 [hep-ph]
[39] Belyaev A, Christensen N D and Pukhov A 2013 *Comput. Phys. Commun.* **184** 1729
[40] Belanger G, Boudjema F, Pukhov A and Semenov A 2010 *Nuovo Cimento.* C **033N2** 111
[41] Kolb E W and Turner M S 1998 *The Early Universe* (Reading, MA: Addison-Wesley)
[42] Fortes E C F S, Machado A C B, Montaño J and Pleitez V 2015 *J. Phys. G: Nucl. Part. Phys.* in press
[43] Krawczyk M, Sokolowska D, Swaczyna P and Swiezewska B 2013 *J. High Energy Phys.* JHEP09 (2013)055
[44] Gustafsson M 2010 (arXiv:1106.1719)