IDMS: Inert Dark Matter Model with a complex singlet

Cesar Bonilla\textsuperscript{1}, Dorota Sokolowska\textsuperscript{2}, J. Lorenzo Diaz-Cruz\textsuperscript{3}, Maria Krawczyk\textsuperscript{2}, Neda Darvishi\textsuperscript{2}

\textsuperscript{1} Instituto de Física Corpuscular (CSIC-Universitat de València), Valencia, Spain.

\textsuperscript{2} University of Warsaw, Faculty of Physics, Warsaw, Poland

\textsuperscript{3} Facultad de Ciencias Fisico-Matematicas, Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

Abstract

Within the Inert Doublet Model (IDM) there is a viable dark matter candidate. This simple model can provide a strong enough first order phase transition, which is required in order to account for the matter-antimatter asymmetry in the Universe (BAU). However, another necessary ingredient is missing, as there is no additional source of CP violation in the IDM, besides the standard CKM phase from the Standard Model. Additional CP violating phase can appear if a complex singlet of $SU(3)_{C} \times SU(2)_{W} \times U(1)_{Y}$ with a non-zero vacuum expectation value is added to the scalar sector of the IDM. We construct the scalar potential of the inert doublet plus singlet model (IDMS), assuming an exact $Z_{2}$ symmetry, with singlet being $Z_{2}$-even. To simplify the model we use a softly broken $U(1)$ symmetry, which allows a reduction of the number of free parameters in the potential. We study the masses and interactions of scalar particles for a few benchmark scenarios. Constraints from collider physics, in particular from the Higgs signal observed at LHC with $M_{h} \approx 125$ GeV are discussed, as well as constraints from the dark matter experiments.
1 Introduction

After so many years of expectations the LHC has found a Standard-Model-like (SM-like) Higgs particle with a mass of \( M_h \approx 125 \text{ GeV} \) \[1, 2\]. Current analysis of the LHC data has been dedicated to the properties of this resonance, with the purpose of determining whether it belongs to the SM or to some of its extensions. In the later case some deviations from the SM expectations are expected.

The LHC has also provided important bounds on the scale of new physics beyond the SM, either through the search for new (probably heavy) particles or by looking for deviations from the SM predictions of properties of the SM particles. Some of the motivations for new physics are related to cosmology, like dark matter (DM) or the baryon asymmetry of the Universe (BAU).

One of the simplest models for a scalar dark matter is the Inert Doublet Model (IDM), a version of a Two Higgs Doublet Model with an exact \( Z_2 \) symmetry \[3\]. Here the SM scalar (Higgs) sector is extended by an inert scalar doublet. There are regions of parameter space where this model can account for the SM-like Higgs particle, and at the same time for the correct relic density of dark matter, while fulfilling direct and indirect DM detection limits, and being in agreement with the LHC results [see e.g. \[4, 5, 6, 7, 8, 9\]].

Furthermore, the IDM can provide a strong first-order phase transition \[10\], which is one of the Sakharov conditions needed to generate a baryon asymmetry of the universe. Another Sakharov requirement, namely the large enough CP violation (CPV), the IDM fails to fulfil. This is because it contains no additional source of CP violation and the only CPV phase from the CKM matrix, as in the SM, is known to be too small to lead to the right amount of BAU. Thus, we need to extend this model with some extra source of CP violation that could allow to address this important problem. In this paper we shall assume that the required
additional CPV is provided by a complex scalar singlet $\chi$, which accompanies the SM-like Higgs and inert doublets, denoted here by $\Phi_1$ and $\Phi_2$, respectively. We shall call this model IDMS (the IDM plus singlet). Our main aim is to study general properties of the model, and to check its agreement with all existing Higgs- and DM data. Detailed investigation of possible tests of the CP violating effects incorporated into the model is beyond the scope of this paper.

The content of this paper is as follows. Section 2 contains the presentation of the general model, in particular the scalar potential. In section 3 we present in detail our model, positivity conditions, the mass eigenstates in the neutral and charged sectors and study the parameter space of the model. Section 4 contains the analysis of Higgs couplings and a comparison with LHC data. In section 5 we present our study of relic density for a dark matter candidate of the model, which is assumed to be the lightest neutral $Z_2$-odd scalar state. Conclusions are presented in section 6, where we also discuss possible implications for neutrino physics. Detailed formulas, benchmark points and values related to the LHC and dark matter analysis are presented in the appendices.

2 The IDMS: The IDM plus a complex singlet

We shall consider a $Z_2$-symmetric model that contains a SM-like Higgs doublet $\Phi_1$, which is involved in a generation of the mases of gauge bosons and fermions, as in the SM. There is also an inert scalar doublet $\Phi_2$, which is odd under a $Z_2$ symmetry. $\Phi_2$ has VEV= 0 and can provide a stable dark matter candidate. Then, we have the neutral complex singlet $\chi$ with hypercharge $Y = 0$ and a non-zero complex VEV.

Singlet $\chi$ can be introduced to play several roles in models with two doublets and a singlet, leading to different scenarios. CP violation can be explicit, provided by the singlet
interaction terms, or spontaneous, if $\langle \chi \rangle \in \mathbb{C}$. The singlet $\chi$ could be even or odd under a $Z_2$ symmetry, and it could mix with the SM-like Higgs doublet and/or with the inert doublet. Furthermore, one could even use the complex singlet to induce all sources of CP violation, including the SM one contained in the CKM mixing matrix, as it was done in Ref. [11].

Here we shall take $\chi$ to be even under a $Z_2$ transformation defined as:

$$Z_2 : \Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2, \text{SM fields} \rightarrow \text{SM fields}, \chi \rightarrow \chi,$$

and allow its mixing only with the neutral components of $\Phi_1$; furthermore, we shall consider the case when the CP symmetry can be violated by a non-zero complex $\langle \chi \rangle$.

The full Lagrangian of the model looks as follows:

$$\mathcal{L} = \mathcal{L}_{gf}^{SM} + \mathcal{L}_{\text{scalar}} + \mathcal{L}_Y(\psi_f, \Phi_1), \quad \mathcal{L}_{\text{scalar}} = T - V,$$

where $\mathcal{L}_{gf}^{SM}$ gives boson-fermion interaction as in the SM, $\mathcal{L}_{\text{scalar}}$ describes the scalar sector of the model, while $\mathcal{L}_Y(\psi_f, \Phi_1)$ – the Yukawa interaction. The kinetic term in $\mathcal{L}_{\text{scalar}}$ has the standard form:

$$T = (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2) + \partial \chi \partial \chi^*,$$

with $D^\mu$ being a covariant derivative for an $SU(2)$ doublet. We take the Yukawa interaction in the form of the Model I in the 2HDM, where only $\Phi_1$ couples to fermions. Within our model the scalar singlet $\chi$ does not couple with the SM fermions and therefore the singlet-fermion interaction are present only through mixing of singlet with the first doublet $\Phi_1$.

In our model only $Z_2$-even fields $\Phi_1$ and $\chi$ acquire vacuum expectation values $v$ and $we^{i\xi}$, respectively, where $v, w \in \mathbb{R}$. We shall use the following field decomposition around the vacuum state $(v, 0, we^{i\xi})$:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}} (v + \phi_1 + i\phi_6) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}} (\phi_4 + i\phi_5) \end{pmatrix}, \quad \chi = \frac{1}{\sqrt{2}} (we^{i\xi} + \phi_2 + i\phi_3).$$
Thus, the $Z_2$ symmetry is not violated spontaneously. Also, $U(1)_{EM}$ is not broken, and there is no mixing between the neutral and charged components. Masses of gauge bosons and fermions are given by the VEV of the first doublet as in the SM, e.g $M_W^2 = g^2 v^2 / 4$ for the $W$ boson.

The full scalar potential of the model can be written as

$$V = V_{IDM} + V_S + V_{DS},$$

(6)

where we have separated the pure doublet and the pure singlet parts (respectively $V_{IDM}$ and $V_S$) and their interaction term $V_{DS}$. The IDM part of the potential, $V_{IDM}$ is given by:

$$V_{IDM} = - \frac{1}{2} \left[m_{11}^2 \Phi_1 \Phi_1^\dagger + m_{22}^2 \Phi_2 \Phi_2^\dagger\right] + \frac{1}{2} \left[\lambda_1 (\Phi_1 \Phi_1^\dagger)^2 + \lambda_2 (\Phi_2 \Phi_2^\dagger)^2\right] + \lambda_3 (\Phi_1 \Phi_1^\dagger) (\Phi_2 \Phi_2^\dagger) + \lambda_4 (\Phi_1 \Phi_2^\dagger) (\Phi_2 \Phi_1^\dagger) + \frac{\lambda_5}{2} \left[(\Phi_1 \Phi_2^\dagger)^2 + (\Phi_2 \Phi_1^\dagger)^2\right].$$

(7)

The most general singlet part of the potential for a complex singlet is equal to:

$$V_S = - \frac{m_3^2}{2} \chi^* \chi - \frac{m_4^2}{2} (\chi^* \chi) + \lambda_{s1} (\chi^* \chi)^2 + \lambda_{s2} (\chi^* \chi)(\chi^* \chi + \chi^2) + \lambda_{s3} (\chi^4 + \chi^4^*) + \kappa_1 (\chi + \chi^*) + \kappa_2 (\chi^3 + \chi^3^*) + \kappa_3 (\chi^* \chi + \chi^* \chi^*).$$

(8)

The doublet-singlet interaction terms are:

$$V_{DS} = \Lambda_1 (\Phi_1 \Phi_1^\dagger) (\chi^* \chi) + \Lambda_2 (\Phi_2 \Phi_2^\dagger) (\chi^* \chi) + \Lambda_3 (\Phi_1 \Phi_1^\dagger) (\chi^* \chi + \chi^2) + \Lambda_4 (\Phi_2 \Phi_2^\dagger) (\chi^* \chi + \chi^2) + \kappa_4 (\Phi_1 \Phi_1^\dagger) (\chi + \chi^*) + \kappa_5 (\Phi_2 \Phi_2^\dagger) (\chi + \chi^*).$$

(9)

We assume that all parameters of $V$ (6) are real.

This potential is $Z_2$-symmetric and the chosen vacuum state (4,5) will not spontaneously break this symmetry, therefore the problem of cosmological domain walls will not arise in this model. In total, there are four quadratic parameters, twelve dimensionless quartic parameters and five dimensionful parameters $\kappa_{1,2,3,4,5}$. The linear term $\kappa_1$ can be removed by a translation of the singlet field, and we will omit it below. It is useful to re-express
dimensionful parameters $\kappa_i$ by dimensionless parameters $\rho_i$ (we consider them being of order $O(1)$) as:

$$\kappa_i = w \rho_i,$$

(10)

with $w$ being an absolute value of the singlet VEV.

One could reduce this general model by invoking additional symmetries besides the imposed $Z_2$ one. In particular, to simplify the model one can apply a global $U(1)$ symmetry, as we discuss below. Similarly, had we chosen to assign a $Z_2$-odd quantum number also to $\chi$ (or if singlet was odd under an additional $Z'_2$ symmetry), it would have also resulted in a variant of the model with a simplified potential, where all terms with an odd number of field $\chi$ would be absent. Obviously, in those cases having a $Z_2$ (or $Z'_2$) symmetric vacuum state would require $\langle \chi \rangle = 0$, and thus there would be no additional CP violation in the model.

3 The constrained IDMS: cIDMS

We will reduce the most general IDMS potential \( (6-9) \) by imposing a global $U(1)$ symmetry:

$$U(1) : \Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow \Phi_2, \chi \rightarrow e^{i\alpha} \chi.$$  

(11)

However, a non-zero VEV $\langle \chi \rangle$ would lead to a spontaneous breaking of this continuous symmetry and appearance of massless Nambu-Goldstone scalar particles, which are not phenomenologically viable. Keeping some $U(1)$-soft-breaking terms in the potential would solve this problem and at the same time would still lead to a reduction of the number of parameters of $V$.

The parameters of the IDMS potential can be divided into the following groups:

1. $U(1)$-symmetric terms: $m^2_{11}, m^2_{22}, m^2_3, \lambda_{1,2,3,4,5}, \lambda_{s1}, \Lambda_{1,2}$.  

2. $U(1)$-soft-breaking terms $m_4^2, \rho_{2,3}, \rho_{4,5}$.

3. $U(1)$-hard-breaking terms $\lambda_{s2}, \lambda_{s3}, \Lambda_{3,4}$.

In what follows we shall consider a potential with a soft-breaking of $U(1)$ symmetry by the singlet cubic terms $\rho_{2,3}$ and quadratic term $m_4^2$ only, neglecting the remaining ones ($\rho_{4,5}$). As it was pointed out $\Phi_1$ is the SM-like Higgs doublet responsible for the EW symmetry breaking and for providing masses of gauge bosons and fermions. Moreover, we also want to use it as a portal for DM interactions with the visible sector, as in the IDM. We shall assume therefore that there is no direct coupling of $\Phi_2$ to $\chi$, thus setting the $U(1)$-invariant term $\Lambda_2 = 0$. The field $\chi$ shall then interact with the DM particles only through mixing with the neutral component of $\Phi_1$.

We are therefore left with the following $U(1)$-symmetric terms ($m_{11}^2, m_{22}^2, m_3^2, \lambda_{1-5}, \lambda_{s1}, \Lambda_1$) and $U(1)$-soft-breaking terms ($m_4^2, \rho_{2,3}$). We shall call our model, the model with this choice of parameters, cIDMS. The cIDMS potential is then given by:

$$V = -\frac{1}{2} \left[ m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 \right] + \frac{1}{2} \left[ \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \right]$$

$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left[ (\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right]$$

$$- \frac{m_3^2}{2} \chi^* \chi + \lambda_{s1}(\chi^* \chi)^2 + \Lambda_1 (\Phi_1^\dagger \Phi_1)(\chi^* \chi)$$

$$- \frac{m_4^2}{2} (\chi^* \chi^2 + \chi^2) + \kappa_2 (\chi^3 + \chi^* \chi^3) + \kappa_3 [\chi (\chi^* \chi) + \chi^*(\chi^* \chi)].$$

### 3.1 Positivity conditions

In order to have a stable minimum, the parameters of the potential need to satisfy the positivity conditions. Namely, the potential should be bounded from below, i.e. should not go to negative infinity for large field values. As this behavior is dominated by the quartic

\footnote{Recall that $\rho_1$ can be removed from (6) by translation of $\chi$.}
terms, the cubic terms will not play a role here. Thus the following conditions will apply to a variety of models that will differ only by their cubic interactions.

We use the method of [12], which uses the concept of co-positivity for a matrix build of coefficients in the field directions. For the cIDMS, the positivity conditions read:

\[ \bar{\lambda}_{1S} = \Lambda_1 + \sqrt{2\bar{\lambda}_1\bar{\lambda}_{s1}} \geq 0, \]

\[ \frac{1}{2}\sqrt{\lambda_1\lambda_2\lambda_{s1}} + [\lambda_3 + \theta[-\lambda_4 + |\lambda_5|](\lambda_4 - |\lambda_5|)]\sqrt{\lambda_{s1}} + \Lambda_1 \sqrt{\frac{\lambda_2}{2}} + \sqrt{\lambda_{12}\lambda_{12S}\lambda_{2S}} \geq 0, \]

where \( \bar{\lambda}_{2S} = \sqrt{2\lambda_2\lambda_{s1}} > 0. \)

### 3.2 Extremum conditions

The minimization conditions lead to the following constraints for three quadratic parameters from \( V \) [12]:

\[ m_{11}^2 = w^2\Lambda_1 + v^2\lambda_1, \] (14)

\[ m_3^2 = v^2\Lambda_1 + 2w^2\lambda_{s1} + \frac{w^2}{\sqrt{2}\cos\xi}(-3\rho_2 + 3\rho_3 + 2\rho_3\cos2\xi), \] (15)

\[ m_4^2 = \frac{w^2}{2\sqrt{2}\cos\xi}(3\rho_2 + \rho_3 + 6\rho_2\cos2\xi). \] (16)

The \( m_{22}^2 \) parameter is not determined by the extremum conditions, just like in the IDM.

The squared-mass matrix \( M_{ij}^2 \), for \( i, j = 1, \ldots, 6 \), is given by:

\[ M_{ij}^2 = \frac{\partial^2V}{\partial\phi_i\phi_j} \bigg|_{\phi_i = \langle \phi_i \rangle, \chi = \langle \chi \rangle}, \] (17)

with \( \phi_i \) being the respective fields from decomposition [14]. This definition along with the normalization defined in [14] gives the proper mass terms of \( M_{\varphi^-\varphi^+}^2 \varphi^- \varphi^+ \) in case of the charged scalar fields and \( M_{\varphi^2}^2 \varphi^2 \) for the neutral scalar fields.
3.3 Comments on vacuum stability

The tree-level positivity conditions \([13]\), which ensure the existence of a global minimum correspond to \(\lambda > 0\) in the Standard Model. It is well known, that the radiative corrections coming from the top quark contribution can lead to negative values of the Higgs self-coupling, resulting in the instability of the SM vacuum for larger energy scales. Full analysis of the stability of the cIDMS potential beyond the tree-level approximation is beyond the scope of this paper. However, it has been shown in Ref. \([7]\) that for the IDM the contributions from additional scalar states will in general lead to the relaxation of the stability bound and allow the IDM to be valid up to the Planck scale. Since cIDMS contains two more scalar states, this condition should hold here as well.

3.4 Mass eigenstates

3.4.1 The neutral sector

The form of the neutral part of the squared-mass matrix \([17]\) for \(\phi_i, (i = 1, \ldots, 6)\) allows us to identify the physical states and their properties:

\[
M^2 = \begin{pmatrix}
M_{\text{mix}}^2 & 0_{(3 \times 3)} \\
0_{(3 \times 3)} & M_H^2 & 0 & 0 \\
0_{(3 \times 3)} & 0 & M_A^2 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]  

(18)

As there is no mixing between four \(Z_2\)-even fields \(\phi_{1,2,3,6}\), and \(\phi_{4,5}\), which are \(Z_2\)-odd, we can divide the particle content of the model into two separate sectors: the \(Z_2\)-even sector, called the Higgs sector, and the \(Z_2\)-odd sector, called the inert sector.

1. The Goldstone field, \(G_z = \phi_6\), is a purely imaginary part of the first doublet \(\Phi_1\).

2. There is a mixing between the singlet \(\chi\) and the real neutral fields of \(\Phi_1\) (namely \(\phi_1, \phi_2\) and \(\phi_3\)) resulting in three neutral scalars \(h_1, h_2, h_3\). Due to the non-zero complex
phase of the singlet VEV \((w e^{i\xi})\) the fields \(h_1, h_2, h_3\) are composed of the states of different CP. Therefore among the possible vertices there are vertices like \(Z Z h_i\) and all \(h_i\) particles couple to fermions. Masses of the these particles depend only on the following parameters of the potential: \(\lambda_1, \Lambda_1, \rho_{2,3}, \lambda_{s1}\).

3. In the inert sector the dark matter candidate from the IDM is stable and it is the lighter of the two neutral components of \(\Phi_2 (\phi_4 \text{ or } \phi_5)\), which we identify as the scalar particles \(H\) and \(A\). Masses of those particles are just like in the IDM:

\[
M_{H}^2 = \frac{1}{2} (-m_{22}^2 + v^2 \lambda_{345}), \quad H = \phi_4,
\]

\[
M_{A}^2 = \frac{1}{2} (-m_{22}^2 + v^2 \lambda_{345}^-), \quad A = \phi_5,
\]

where \(\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5\), \(\lambda_{345}^- = \lambda_3 + \lambda_4 - \lambda_5\). Notice, that the IDM relation for masses still holds:

\[
\lambda_5 = \frac{M_{H}^2 - M_{A}^2}{v^2}.
\]

If \(\lambda_5 < 0\) then \(H\), as a neutral lighter state, is our dark matter candidate. Since \(Z_2\) symmetry is exact in our model, the \(Z_2\)-odd particles have limited gauge and scalar interactions (they interact in pairs only) and they do not couple to fermions. Masses of inert particles depend only on \(\lambda_{3,4,5}\) and \(m_{22}^2\). Those parameters do not influence masses of the Higgs particles from the \(Z_2\)-even sector. In that sense, masses of particles from the Higgs and inert sectors can be studied separately. On this level, the only connection between parameters from those two sectors is through the positivity constraints. As in the IDM, \(\lambda_2\) does not influence the mass sector and it appears only as a quartic coupling between the \(Z_2\)-odd particles.
3.4.2 The charged sector

The $Z_2$-odd charged scalar $H^\pm$ comes solely from the second doublet, as in the IDM; its mass is given by

$$M^2_{H^\pm} = \frac{1}{2}(-m^2_{22} + v^2\lambda_3). \quad (22)$$

Notice, that the mass relations for the $Z_2$-odd sector from the IDM still hold, namely

$$M^2_H = M^2_{H^\pm} + \frac{v^2(\lambda_4 + \lambda_5)}{2}, \quad M^2_A = M^2_{H^\pm} + \frac{v^2(\lambda_4 - \lambda_5)}{2}. \quad (23)$$

Neutral particle $H$ is a DM candidate, therefore $\lambda_4 + \lambda_5 < 0$, resulting in $M_H < M_{H^\pm}$.

If we allow an additional mixing between $\Phi_2$ and $\chi$ through a non-zero $\Lambda_{2,4}$ or $\rho_5$ then the squared-mass formulas are modified as $M^2_{H,A,H^\pm} \rightarrow M^2_{H,A,H^\pm} + \Delta$, with $\Delta = \frac{1}{2}w^2(\Lambda_2 + 2\Lambda_4 \cos 2\xi + 2\sqrt{2}\rho_5 \cos \xi)$. Still, the IDM relations (21) and (23) hold.

3.5 Physical states in the Higgs sector

The mass matrix that describes the singlet-doublet mixing, in the basis of neutral fields $(\phi_1, \phi_2, \phi_3)$, is given by:

$$M^2_{mix} = \begin{pmatrix} \mu_{11} & \mu_{12} & \mu_{13} \\ \mu_{12} & \mu_{22} & \mu_{23} \\ \mu_{13} & \mu_{23} & \mu_{33} \end{pmatrix}, \quad (24)$$

where matrix elements $\mu_{ij}$ are

$$\mu_{11} = \lambda_1 v^2, \quad (25)$$

$$\mu_{12} = wv\Lambda_1 \cos \xi, \quad (26)$$

$$\mu_{13} = wv\Lambda_1 \sin \xi, \quad (27)$$

$$\mu_{22} = \frac{w^2}{2\cos \xi} \left(3\sqrt{2}\rho_2 + \sqrt{2}\rho_3(1 + 2\cos 2\xi) + \lambda_{s1}(3\cos \xi + \cos 3\xi)\right), \quad (28)$$

$$\mu_{23} = w^2 \left(\sqrt{2}(-3\rho_2 + \rho_3) + 2\lambda_{s1} \cos \xi\right) \sin \xi, \quad (29)$$

$$\mu_{33} = 2w^2 \sin^2 \xi \lambda_{s1}. \quad (30)$$
Only if $\Lambda_1 \neq 0$ and $w, \sin \xi \neq 0$ then there is a mixing between states of different CP properties $\phi_1$ or $\phi_2$ and $\phi_3$ (entries $\mu_{13}$ and $\mu_{23}$ respectively).

Diagonalization of $M_{\text{mix}}^2$ \cite{24} gives the mass eigenstates, which can be also obtained by the rotation of the field basis:

$$
\begin{pmatrix}
 h_1 \\
 h_2 \\
 h_3
\end{pmatrix} = R
\begin{pmatrix}
 \phi_1 \\
 \phi_2 \\
 \phi_3
\end{pmatrix}, \quad \tilde{M}^2 = R M_{\text{mix}}^2 R^T = \text{diag}(M_{h_1}^2, M_{h_2}^2, M_{h_3}^2).
$$

(31)

The rotation matrix $R = R_1 R_2 R_3$ in principle depends on three mixing angles ($\alpha_1, \alpha_2, \alpha_3$). The individual rotation matrices are given by (here and below $c_i = \cos \alpha_i, s_i = \sin \alpha_i$):

$$
R_1 = \begin{pmatrix}
 c_1 & s_1 & 0 \\
 -s_1 & c_1 & 0 \\
 0 & 0 & 1
\end{pmatrix}, \quad R_2 = \begin{pmatrix}
 c_2 & 0 & s_2 \\
 0 & 1 & 0 \\
 -s_2 & 0 & c_2
\end{pmatrix},
$$

(32)

and

$$
R_3 = \begin{pmatrix}
 1 & 0 & 0 \\
 0 & c_3 & s_3 \\
 0 & -s_3 & c_3
\end{pmatrix}.
$$

(33)

All $\alpha_i$ vary over an interval of length $\pi$. The full rotation matrix depends on the mixing angles in the following way:

$$
R = R_1 R_2 R_3 = \begin{pmatrix}
 c_1 c_2 & c_3 s_1 - c_1 s_2 s_3 & c_1 c_3 s_2 + s_1 s_3 \\
 -c_2 s_1 & c_1 c_3 + s_1 s_2 s_3 & -c_3 s_1 s_2 + c_1 s_3 \\
 -s_2 & -c_2 s_3 & c_2 c_3
\end{pmatrix}.
$$

(34)

The inverse of $R$ can be used to obtain the reverse relation between $h_i$ and $\phi_i$:

$$
R^{-1} = \begin{pmatrix}
 c_1 c_2 & -c_2 s_1 & -s_2 \\
 c_3 s_1 - c_1 s_2 s_3 & c_1 c_3 + s_1 s_2 s_3 & -c_2 s_3 \\
 c_1 c_3 s_2 + s_1 s_3 & -c_3 s_1 s_2 + c_1 s_3 & c_2 c_3
\end{pmatrix}.
$$

(35)

The two important relations can be read from those rotation matrices, namely:

$$
h_1 = c_1 c_2 \phi_1 + (c_3 s_1 - c_1 s_2 s_3) \phi_2 + (c_1 c_3 s_2 + s_1 s_3) \phi_3
$$

(36)
and
\[
\phi_1 = c_1 c_2 h_1 - c_2 s_1 h_2 - s_2 h_3. \tag{37}
\]

They describe the composition of the SM-like Higgs boson \(h_1\), in terms of real components \(\phi_1\) and \(\phi_2\), which provide a CP-even part, as well as the \(\phi_3\) component, which signals the CP violation in the model. Equivalently, one can look at it as the modification of the real component of the SM-like Higgs doublet \(\Phi_1\) from the cIDMS with respect to the SM and the IDM.

Especially important is the first element both in \(R\) and \(R^{-1}\) equal to:
\[
R_{11} = R_{11}^{-1} = c_1 c_2. \tag{38}
\]

This matrix element gives the relative modification of the interaction of the Higgs boson \((h_1)\) with respect to the IDM, and will be important both in the LHC analysis (section 4), and in the DM studies (sec. 5).

### 3.6 Parameter space in the Higgs sector

In what follows we shall numerically analyze the allowed regions of parameters of our model. In scans the positivity (13) and perturbativity conditions, where all quartic parameters in the potential are taken to be below 1, are fulfilled.

As LHC data is favouring a SM-like interpretation of the observed 125 GeV Higgs signal, we shall require that the lightest neutral Higgs state comes predominantly from the doublet \(\Phi_1\). If there was no \(\Phi_1 - \chi\) mixing, then the SM-like Higgs boson’s mass would have been given by \(M_{h_1}^2 = v^2 \lambda_1 \Rightarrow \lambda_1 \approx 0.23\) (for \(v = 246\) GeV). We are going to consider the variation of \(\lambda_1\) in range:
\[
0.2 < \lambda_1 < 0.3, \tag{39}
\]
and demand that the mass of the lightest Higgs particle $h_1$ lies in range [124.69, 125.37] GeV.\footnote{The considered mass range [124.69, 125.37] GeV is in the $2\sigma$ range in agreement with the newest LHC data \cite{13, 14} for the Higgs mass.} The additional two Higgs scalars are heavier, we take

$$M_{h_3} > M_{h_2} > 150 \text{ GeV}. \quad (40)$$

Remaining parameters of the Higgs sector change in the following ranges:

$$-1 < \Lambda_1 < 1, \quad 0 < \lambda_{s1} < 1, \quad -1 < \rho_{2,3} < 1, \quad 0 < \xi < 2\pi. \quad (41)$$

Parameters from the inert sector, i.e. $\lambda_{2-5}, m_{22}^2$ do not directly influence values of masses of Higgs particles \cite{24, 30}. One must remember however, that allowed values of $\lambda_{2-5}$ are related to the ranges of Higgs parameters through the positivity constraints \cite{13}. In the scans, inert parameters change in the range allowed by the perturbativity constraints, with $H$ being the DM candidate (see sec.3.7):

$$0 < \lambda_2 < 1, \quad -1 < \lambda_{3,4} < 1, \quad -1 < \lambda_5 < 0. \quad (42)$$

We performed the scanning for $w \sim v = 246$ GeV, in particular for $w = 300, 500, 1000$ GeV. However, after noting that the results do not depend strongly on the exact value of this parameter, we opted here to present results with plots only for $w = 300$ GeV.

- Fig. 1a and 2a show the allowed regions in the planes ($\lambda_{s1}, \Lambda_1$) and ($\lambda_{s1}, \rho_2$). Here we can see that there is a lower bound on $\lambda_{s1}$ of order 0.1.
Figure 1: Correlations between parameters in the Higgs sector. Results of scanning for \( w = 300 \) GeV, with ranges of parameters defined by (41). Notice the limited range of \( \Lambda_1 \) and the lower limit for \( \lambda_{s1} \).

- Results of scanning presented in Fig. 1a and Fig. 1b also show that the range of \( \Lambda_1 \) is further limited with respect to the initial assumptions (41), and that good solutions require \( |\Lambda_1| \lesssim 0.25 \). Recall that this parameter describes mixing between \( \Phi_1 \) and \( \chi \), effectively giving the non-SM contribution to the SM-like Higgs doublet.

Figure 2: Correlations between parameters in the Higgs sector. Results of scanning for \( w = 300 \) GeV, with ranges of parameters defined by (41). Again, limit for \( \lambda_{s1} \) appears. Points in the \( (\rho_2, \rho_3) \) plane are almost uniformly distributed.

- There is a correlation between a sign of \( \rho_2 \) (but not of \( \rho_3 \)) and the value of \( \xi \) as presented
in Fig. 3a and Fig. 3b respectively. This correlation is related to the positivity of $M_{h_2}^2$ – by taking a wrong assignment of $(\rho_2, \xi)$ pair, e.g. $\pi/2 < \xi < 3\pi/2$ and $\rho_2 > 0$, we end up with negative $M_{h_2}$.

Figure 3: Correlations between parameters in the Higgs sector. Results of scanning for $w = 300$ GeV, with ranges of parameters defined by (41). Notice the correlation present in $(\rho_2, \xi)$, but not in $(\rho_3, \xi)$.

• $\xi$ was initially varied in range $[0, 2\pi]$. We found that there is a symmetry in the plans for reflection with respect to $\xi \sim \pi$, as seen in Figs. 1b, 3a and Fig. 3b. Therefore, remaining analysis in this paper is limited to values of $\xi \in [0, \pi]$ without affecting the results.

• Fig. 4 displays $M_{h_2, h_3}$ versus $\lambda_{s_1}$. Here we see that the maximum allowed value of $M_{h_2}$ depends on the value of $\lambda_{s_1}$ (Fig. 4a): for $\lambda_{s_1} = 0.2$ we can expect masses in range $150 < M_{h_2} < 200$ GeV, while for $\lambda_{s_1} = 1$ the upper limit goes up to about 430 GeV. Allowed values for the mass of $h_3$ are higher than for $h_2$, $170$ GeV $< M_{h_3} < \mathcal{O}(10$ TeV), and are almost independent of $\lambda_{s_1}$. Fig 4b shows that the mass of $h_3$ lays in the range $170 < M_{h_3} < 2000$ GeV.
Figure 4: Correlations between parameters in the Higgs sector. Results of scanning for \( w = 300 \text{ GeV} \), with ranges of parameters defined by (41). Upper bound for \( M_{h_2} \) strongly depends on the value of \( \lambda_{s1} \), but there is no such effect of \( M_{h_3} \).

- Fig. 5 displays \( M_{h_2}, M_{h_3} \) versus \( \rho_2 \). Now the allowed range for the mass of \( h_2 \) is almost independent of \( \rho_2 \) and is given by \( 150 < M_{h_2} < 430 \text{ GeV} \), while the allowed masses for \( h_3 \) go from \( 170 < M_{h_3} < 2000 \text{ GeV} \) for \( \rho_2 = 0 \), and are reduced to \( 600 < M_{h_3} < 2000 \text{ GeV} \) for \( \rho_2 = \pm 1 \).

Figure 5: Correlations between parameters in the Higgs sector. Results of scanning for \( w = 300 \text{ GeV} \), with ranges of parameters defined by (41). Notice the seagull-like shape for the lower limit for \( M_{h_3} \), but not for \( M_{h_2} \).

- Fig. 6 displays \( M_{h_2}, M_{h_3} \) versus \( \xi \). Here we observe a symmetry for reflection at
$\xi \sim \pi/2$. The allowed range, which is $150 < M_{h_2} < 200$ GeV for $\xi = 0.5$, extends up to $150 < M_{h_2} < 430$ GeV for $\xi = 1.6$. Very high mass values for $h_3$ can be obtained for $\xi \sim \pi/2$ (up to 2 TeV).

![Figure 6: Correlations between parameters in the Higgs sector. Results of scanning for $w = 300$ GeV, with ranges of parameters defined by (41).](image)

### 3.7 Parameter space in the inert sector

As discussed in section 3.4.1, masses of $Z_2$-odd particles are given by a different set of parameters than masses of $Z_2$-even particles, which were analyzed in the previous subsection. Here, relevant are three quartic parameters, $\lambda_{3,4,5}$, and one quadratic parameter $m_{Z_2}^2$. The remaining quartic parameter, $\lambda_2$, appears only in the quartic interaction of $Z_2$-odd particles and is therefore not constrained by the analysis of the mass spectrum. However, we expect that – as in the IDM – combined unitarity, perturbativity and global minimum conditions may provide constraints for this, otherwise unlimited, parameter [15].

Masses of $Z_2$-odd scalars, and therefore parameters of the potential given by relations (21) and (23), are already constrained by experimental and theoretical results.

1. Measurements done at LEP limit the invisible decays of $Z$ and $W^\pm$ gauge bosons,
require that there is no decay of $W^\pm, Z$ into inert particles resulting in [16, 17]:

$$M_{H^\pm} + M_{H,A} > M_{W^\pm}, \quad M_H + M_A > M_Z, \quad 2M_{H^\pm} > M_Z.$$  \hspace{1cm} (43)

2. Searches for charginos and neutralinos at LEP have been translated into limits of region of masses in the IDM [17] excluding

$$M_A - M_H > 8 \text{ GeV if } M_H < 80 \text{ GeV } \land M_A < 100 \text{ GeV}.$$  \hspace{1cm} (44)

We shall adopt the same limit for inert particles in the studied cIDMS.

3. Note that, as in the IDM, the value of $M_{H^\pm}$ provides limits for $m_{22}^2$, which is not constrained by the extremum conditions. Demanding that $M_{H^\pm} > 0$ results in $m_{22}^2 < \lambda_3 v^2$, which for discussed range of $-1 \leq \lambda_3 \leq 1$ reduces to $m_{22}^2 < v^2$. This constraint is modified by taking into account the model-independent limit for the charged scalar mass [18]:

$$M_{H^\pm} > 70 - 90 \text{ GeV } \Rightarrow m_{22}^2 \lesssim 5 \cdot 10^4 \text{ GeV}^2$$  \hspace{1cm} (45)

Fig. [7] shows the correlation between the charged-scalar mass and $m_{22}^2$. Large values of $M_{H^\pm}$ correspond to large values of $-m_{22}^2$.

![Figure 7: Charged scalar mass $M_{H^\pm}$ as a function of $m_{22}^2$.](image)

4. Mass splittings between the $Z_2$-odd particles are given by combinations of $\lambda_4, \lambda_5$ parameters, which are constrained by the perturbativity conditions. If we demand that
$|\lambda_{3,4,5}| < 1$ then in the heavy mass regime all particles will have similar masses, as they are all driven to high scales by the value of $-m^2_{22}$ \cite{23}. This is visible in Fig. 8. Notice that mass splitting of the order of 200 GeV is allowed for the lighter particles.

![Figure 8: Left: Relation between $M_H$ and $M_A$. Right: Relation between $M_H$ and $M_{H^\pm}$. Both correlations for random scanning with $|\lambda_{3,4,5}| < 1$ and $|m^2_{22}| < 10^6$ GeV$^2$.](image)

5. Electroweak precision measurements provide strong constraints for New Physics beyond the SM. In particular, additional particles may introduce important radiative corrections to gauge boson propagators. Those corrections can be parameterized by the oblique parameters $S$, $T$ and $U$. The value of these parameters will be influenced both by the presence of extra (heavy) Higgses present in the cIDMS and by inert particles $H^\pm$, $H$ and $A$. $T$ is sensitive to the isospin violation, i.e. it measures the difference between the new physics contributions of neutral and charged current processes at low energies, while $S$ gives new physics contributions to neutral current processes at different energy scales. $U$ is generally small in new physics models. The latest values of the oblique parameters, determined from a fit with reference mass-values of top and Higgs boson $M_{t,ref} = 173$ GeV and $M_{h,ref} = 125$ GeV are \cite{19}:

$$S = 0.05 \pm 0.11, \quad T = 0.09 \pm 0.13, \quad U = 0.01 \pm 0.11. \quad (46)$$

In our work we have checked the compatibility of our benchmark points with the $3\sigma$
bounds on $S$ and $T$, following the method described in [20]. For detailed formulas see Appendix [3]. Specific values for given sets of parameters are presented in Table 2 in Appendix D. In general, we took the IDM results as the guidance points for our analysis, and the cIDMS represents the same behaviour: additional heavy particles, including the heavy Higgses, can be accommodated in the model without violating EWPT constraints.

6. Measurements of invisible decays of the SM-like Higgs at the LHC set very strong constraints on Higgs-portal type of DM models [see e.g. [21] and detailed use of constraints in [8] for the IDM, or [22] for the 3HDM]. In general, a DM candidate with mass below approximately 53 GeV annihilating mainly into $b\bar{b}$ through the Higgs exchange cannot be in agreement with the LHC limits and relic density constraints. The remaining region, $53\text{ GeV} \lesssim M_H \lesssim 62.5\text{ GeV}$, corresponds to the Higgs-resonance, and the tree-level behaviour is roughly the same in all Higgs-portal-type DM models. In principle, calculations in this region require loop corrections both for the annihilation cross-section, and the scattering cross-section, which is beyond the scope of this work. Therefore, in our analysis we will focus on $M_H > M_{h_1}/2$, i.e. region where Higgs invisible decay channels are closed and comment on region $M_H < M_{h_1}/2$ in sections 4 and 5 for completeness.

7. For $M_H > M_{h_1}/2$, where $h_1$ is the SM-like Higgs particle, all invisible decay channels are closed and the most important LHC constraint is now the measured value of $h \rightarrow \gamma\gamma$ signal strength, which will be discussed in detail in the next section.

Further constraints for the DM candidate $H$ come obviously from the astrophysical measurements of DM relic density, and direct and indirect detection. Those will be discussed in section 5.
4 LHC constraints on Higgs parameters in cIDMS

4.1 Higgs signal strength in cIDMS

Further constraints on the parameters of our model (cIDMS) can be obtained by comparing the light Higgs signal ($h_1$), and the one arising from the SM, with the LHC results. This is done by introducing the following signal strength:

$$\mathcal{R}_{XX} = \frac{\sigma(gg \rightarrow h_1)}{\sigma(gg \rightarrow \phi_{SM})} \frac{\text{BR}(h_1 \rightarrow XX)}{\text{BR}(\phi_{SM} \rightarrow XX)},$$

(47)

for $X = \gamma, Z, ...$, assuming the gluon fusion is the dominant Higgs production channel at the LHC.

Within the narrow-width approximation, the expression for $\mathcal{R}_{XX}$ reduces to:

$$\mathcal{R}_{XX} = \frac{\Gamma(h_1 \rightarrow gg)}{\Gamma(\phi_{SM} \rightarrow gg)} \frac{\text{BR}(h_1 \rightarrow XX)}{\text{BR}(\phi_{SM} \rightarrow XX)}.$$

(48)

In our model the couplings of the lightest Higgs particle ($h_1$) with vector bosons and top quark get modified, as compared with the SM, only by a factor $R_{11}$ (where $R_{11}$ is the (11) element of $R^{-1}$ defined by (38)).

Thus we can write the Higgs ($h_1$) decay width into gluons as follows:

$$\Gamma(h_1 \rightarrow gg) = R_{11}^2 \Gamma(\phi_{SM} \rightarrow gg).$$

(49)

Similarly, for the Higgs boson decay into vector bosons ($V = Z, W$) we have

$$\Gamma(h_1 \rightarrow VV^{\star}) = R_{11}^2 \Gamma(\phi_{SM} \rightarrow VV^{\star}).$$

(50)

The one-loop coupling of $h_1$ to photons receives contributions mainly from the W boson and top quark, as well as the charged scalar $H^\pm$ from the inert sector, so the amplitude can
be written as

\[ A(h_1 \rightarrow \gamma \gamma) = R_{11}(A_W^{SM} + A_t^{SM}) + A_{H^\pm}. \]  (51)

Therefore, the decay widths into two photons and into a photon plus a Z boson, are given, respectively, by

\[ \Gamma(h_1 \rightarrow \gamma \gamma) = \Gamma(\phi_{SM} \rightarrow \gamma \gamma)|1 + \eta_1|^2, \]  (52)

\[ \Gamma(h_1 \rightarrow Z\gamma) = R_{11}^2|1 + \eta_2|^2\Gamma(\phi_{SM} \rightarrow Z\gamma), \]  (53)

where

\[ \eta_1 = \frac{g_{h_1 H^+ H^-} v}{2R_{11} M_{H^\pm}^2} \frac{A_{H^\pm}}{(A_W^{SM} + A_t^{SM})}, \quad \eta_2 = \frac{g_{h_1 H^+ H^-} v}{2R_{11} M_{H^\pm}^2} \left( \frac{A_{H^\pm}}{(A_W^{SM} + A_t^{SM})} \right). \]  (54)

The triple coupling \( \lambda_{h_1 H^+ H^-} \) is given by

\[ g_{h_1 H^+ H^-} = v\lambda_3 R_{11}, \]  (55)

meaning it is also modified with respect to the IDM by a factor of \( R_{11} \).

As a good approximation\(^4\) in the total SM width of the Higgs boson we can neglect the contributions coming from the Higgs decay into \( Z\gamma \) and \( \gamma \gamma \).

The total Higgs decay width can be significantly modified with respect to the SM if \( h_1 \) can decay invisibly into inert particles. The partial decay width for the invisible channels \( h_1 \rightarrow \varphi \varphi \), where \( \varphi = A, H \), is:

\[ \Gamma(h_1 \rightarrow \varphi \varphi) = \frac{g_{h_1 \varphi \varphi}^2}{32\pi M_{h_1}} \left( 1 - \frac{4M_{\varphi}^2}{M_{h_1}^2} \right)^{1/2}, \]  (56)

with

\[ g_{h_1 A A} = \lambda_{345} v R_{11} \quad \text{and} \quad g_{h_1 H H} = \lambda_{345} v R_{11}. \]

\(^3\)See Appendix A and references therein for more details.

\(^4\)Bear in mind that this approximation is established in order to obtain some analytical expressions for the corresponding ratios, \( R_{\gamma \gamma}, R_{Z\gamma} \) and \( R_{ZZ} \) whose results will guide our dark matter analysis.
Therefore, including regions of masses where Higgs-invisible decays could take place, the total width of the Higgs boson in the cIDMS is given by

$$\Gamma_{tot} \approx R_{11}^2 \Gamma_{tot}^{SM} + \Gamma_{inv},$$

(57)

where

$$\Gamma_{inv} = \sum_{\phi_i} \Gamma(h_1 \rightarrow \phi_i \phi_i) \text{ for } M_{\phi_i} < M_{h_1}/2, \phi_i = A, H.$$  

(58)

Finally, the signal strengths from Eq.(48) can be written as follows,

$$R_{ZZ} = R_{11}^2 \zeta^{-1}, \quad R_{\gamma\gamma} = R_{11}^2 |1 + |\eta_1|^2| \zeta^{-1}, \quad R_{Z\gamma} = R_{11}^2 |1 + |\eta_2|^2| \zeta^{-1},$$

(59)

where $\zeta$ is defined as

$$\zeta \equiv 1 + \frac{\Gamma_{inv}}{R_{11}^2 \Gamma_{tot}^{SM}}$$

(60)

which becomes important when the Higgs is decaying invisibly, otherwise $\zeta^{-1} = 1$.

For the cIDMS case $R_{11} = c_1 c_2$, where $c_1 = \cos \alpha_1$ and $c_2 = \cos \alpha_2$ are defined by the rotation angles in the scalar sector, Eq.(34), and thus

$$R_{ZZ} = c_1^2 c_2^2 \zeta^{-1}, \quad R_{\gamma\gamma} = c_1^2 c_2^2 |1 + |\eta_1|^2| \zeta^{-1}, \quad R_{Z\gamma} = c_1^2 c_2^2 |1 + |\eta_2|^2| \zeta^{-1}.$$  

(61)

Notice that there is a limit of $R_{ZZ}$, i.e. $R_{ZZ} \leq 1$. It is not possible to enhance this decay with respect to the SM. $R_{\gamma\gamma}$ and $R_{Z\gamma}$ can be bigger than 1 if there is a constructive interference between the SM and the cIDMS contributions.
4.2 Numerical analysis

As discussed in sections 3.6 and 3.7 we accept a value of $M_h$ if it lies within the range (124.69, 125.37) GeV, while the rest of the parameters are allowed to run over the following ranges,

$$0.2 \leq \lambda_1 \leq 0.3, \quad -1 \leq \Lambda_1, \lambda_{3,4}, \rho_{2,3} \leq 1, \quad 0 \leq \xi \leq \pi,$$

$$0 < \lambda_s < 1, \quad 0 < \lambda_2 < 1, \quad -1 < \lambda_5 < 0,$$

and $|m_{22}^2| < 10^6 (\text{GeV})^2$.

with $v = 246$ GeV and $w = 300$ GeV.

From Fig. 9 it is clear that the ratios $R_{\gamma\gamma}$, $R_{Z\gamma}$ and $R_{ZZ}$ can present deviations from the SM value up to 20%. Fig. 9a shows the correlation between $R_{\gamma\gamma}$ and $R_{Z\gamma}$, while Fig. 9b correspond to $R_{\gamma\gamma}$ and $R_{ZZ}$.

![Figure 9: (a) Correlation between $R_{\gamma\gamma}$ and $R_{Z\gamma}$. (b) Correlation between $R_{\gamma\gamma}$ and $R_{ZZ}$.](image)

If $R_{\gamma\gamma} < 1$ then both $R_{Z\gamma}$ and $R_{ZZ}$ are correlated with $R_{\gamma\gamma}$, $R_{\gamma\gamma} \sim R_{Z\gamma}$ and $R_{\gamma\gamma} \sim R_{ZZ}$. Notice that there is a possibility of enhancement of both $R_{\gamma\gamma}$ and $R_{Z\gamma}$. This is in agreement with the IDM, where a correlation between enhancement in $\gamma\gamma$ and $Z\gamma$ channels exists [23].

$R_{\gamma\gamma}$ and $R_{Z\gamma}$ as functions of $M_{H^\pm}$ are shown in Fig. 10a and Fig. 10b, respectively. For smaller masses of the charged scalar there is a possibility of enhancement of both $R_{\gamma\gamma}$ and
\( \mathcal{R}_{Z\gamma} \). For heavier \( M_{H^\pm} \) the maximum values tend to the SM value, however deviation up to 20 \%, i.e. \( \mathcal{R}_{\gamma\gamma,Z\gamma} \approx 0.8 \), is possible. Note that the situation is similar to the one from the IDM, where significant enhancement, e.g. \( \mathcal{R}_{\gamma\gamma} = 1.2 \), was possible only if \( M_{H^\pm} \lesssim 150 \text{ GeV} \), and for heavier masses \( \mathcal{R}_{\gamma\gamma} \to 1 \) [23].

![Figure 10: (a) \( \mathcal{R}_{\gamma\gamma} \) as function of \( M_{H^\pm} \). (b) \( \mathcal{R}_{Z\gamma} \) as function of \( M_{H^\pm} \). Note that the upper limit for \( M_{H^\pm} \) comes from the lower limit for \( m_{22}^2 \) from set (62).](image1)

![Figure 11: (a) \( \mathcal{R}_{\gamma\gamma} \) as function of \( M_H \). (b) \( \mathcal{R}_{Z\gamma} \) as function of \( M_H \).](image2)

Similar result is presented in Fig. 12 which depicts \( \mathcal{R}_{\gamma\gamma} \) as function of the dimensionful parameter \( m_{22}^2 \). Significant enhancement is possible only for small values of \( |m_{22}^2| \), which correspond to small values of \( M_{H^\pm} \). For large negative values of \( m_{22}^2 \), i.e. heavy masses...
of all $Z_2$-odd scalars, the preferred value of $\mathcal{R}_{\gamma\gamma}$ is close to the SM value. Then the heavy particles effectively decouple from the SM sector and their influence on the SM observables is minimal, as expected. This effect it also visible in the IDM.

![Figure 12: $\mathcal{R}_{\gamma\gamma}$ as function of $m_{22}^2$.](image)

4.3 Comment on invisible Higgs decays

As it was already mentioned in section 3.7 measurement of Higgs invisible decays is a powerful tool to constrain models, which contain additional scalar particles with couple to the SM-like Higgs $h_1$ and have masses smaller than $M_{h_1}/2$. The partial decay width of Higgs into invisible particles, for example a DM candidate from the cIDMS, is given by (56), and therefore depends on the DM candidate’s mass and its coupling to the Higgs.

The cIDMS acts here as a standard Higgs-portal type of DM model and we obtain results known already for the IDM. Figure 13 shows the relation between the coupling of DM candidate to Higgs (which is $c_1c_2\lambda_{345}$ with $c_1c_2 \approx 0.99$ for all considered benchmark points) and $M_H$ assuming that $Br(h_1 \rightarrow inv)$ is smaller than 0.37 (which is the value from ATLAS, denoted by dashed line [24]) and 0.2 (which is the value coming from global fit analysis, solid line [25]).
Figure 13: Constraints for $\lambda_{345}$ from measurements of Higgs invisible decays branching ratio, with the assumption that only $h_1 \to HH$ channel is open. Solid line: $Br(h \to inv) = 0.2$, dashed line: $Br(h \to inv) = 0.37$.

If we demand that $Br(h_1 \to inv) < 0.37$ allowed region of DM-Higgs coupling is $c_1 c_2 \lambda_{345} \lesssim 0.02$. For $Br(h_1 \to inv) < 0.20$ we obtain $c_1 c_2 \lambda_{345} \lesssim 0.015$. This limit will be combined with the relic density measurements in section 5 and it will provide strong constrain, comparable with the one obtained from DM direct detection searches, for low DM mass region.

In Fig. 14a we see that for a 20% deviation of $R_{\gamma\gamma}$ from the SM model value, the invisible branching ratio is actually $Br(h_1 \to inv) < 0.20$. On the other hand, Fig. 14b shows that when the invisible channels are open, the dimensionless parameter $\lambda_{345}$ should be small (as mentioned above) in order to get an invisible branching ratio below 20%. Notice that when the invisible decay channel of the Higgs is closed, that is $Br(h_1 \to inv) = 0$, then $\lambda_{345} \gtrsim -0.5$. In both figures the horizontal line at $Br(h_1 \to inv) = 0.2$ should be understood as a reference point, so that all the points above it are ruled out by current experiment results.
Figure 14: (a) $\text{Br}(h_1 \rightarrow \text{inv})$ as a function of $R_{\gamma\gamma}$. (b) $\text{Br}(h_1 \rightarrow \text{inv})$ as a function of $\lambda_{345}$. In both panels, all the points above $\text{Br}(h_1 \rightarrow \text{inv}) = 0.2$ are ruled out by current experiment results.

## 5 Dark Matter in the cIDMS

In this section we will discuss properties of DM in the model. Because we can treat the cIDMS as an extension of the IDM, we will start with the brief description of DM phenomenology of the later. In both models $H$ is a DM candidate if $\lambda_5 < 0$. In the IDM the DM annihilation channels that are dominant for the DM relic density are $HH \rightarrow h \rightarrow f \bar{f}$ for $M_H \lesssim M_W$ and $HH \rightarrow WW$ and $HH \rightarrow h \rightarrow WW$ for $M_H \gtrsim M_W$. If the mass splittings $M_A - M_H$ or $M_{H^\pm} - M_H$ are small then also the coannihilation channels $HA(H^\pm) \rightarrow Z(W^\pm) \rightarrow f f'$ play an important role.

Regions of masses and couplings that correspond to the proper relic density have been studied in many papers (see e.g. [5, 6, 16, 26, 27, 28, 29]). In general, there are four regions of DM mass where the measured relic density can be reproduced: light DM particles with mass below 10 GeV, medium mass regime of 50 – 80 GeV with two distinctive regions: with or without coannihilation of $H$ with the neutral $Z_2$-odd particle $A$, medium mass region 80 – 150 GeV with very large mass splittings, and heavy DM of mass larger than roughly...
550 GeV, where all inert particles have almost degenerate masses and so coannihilation processes between all inert particles are crucial. Those regions are further constrained or excluded (as it is the case with the low DM mass region) by direct and indirect detection experiments, and by the LHC data (see e.g. [8, 7, 9] for recent results).

Addition of the singlet field $\chi$ changes this picture, although certain properties of the IDM are kept. In our model there is no direct coupling between the inert doublet $\Phi_2$ and the singlet $\chi$, and the only interaction is through mixing of $\chi$ with the first doublet $\Phi_1$. This means, that the inert particles’ interaction with gauge bosons is like in the IDM, while the inert scalars-Higgs interaction changes with respect to the IDM in the way. The IDM Higgs particle $h$ corresponds in our case to $\phi_1$, so $h \rightarrow \phi_1$, where $\phi_1 = \beta_1 h_1 + \beta_2 h_2 + \beta_3 h_3$ is given by the mixing parameters in (37), and obviously $\sum_{i=1}^{3} \beta_i^2 = 1$. The IDM case corresponds to $\beta_{2,3} \rightarrow 0$. The important processes for the cIDMS are now:

\[ HH \rightarrow h_i \rightarrow f \bar{f}, \quad HH \rightarrow h_i \rightarrow WW(ZZ), \quad (63) \]
\[ HH \rightarrow WW, \quad (64) \]
\[ HA(H^\pm) \rightarrow Z(W^\pm) \rightarrow f f', \quad (65) \]

with couplings $g_{h_i HH} = \beta_i g_{h_i HH}^{IDM}$, $g_{h_i f f} = \beta_i g_{h_i f f}^{IDM}$, $g_{h_i XX}^{IDM}$ being the respective couplings of $h$ to $HH$ and $f \bar{f}$ in the IDM. Following sum rules hold:

\[ \sum_{i=1}^{3} g_{h_i HH}^2 = (g_{h HH}^{IDM})^2 = \lambda_{345}^2, \quad (66) \]

\[ \sum_{i=1}^{3} g_{h_i f f}^2 = (g_{h f f}^{IDM})^2. \]

Since both $g_{h_i HH}$ and $g_{h_i f f}$ have an extra $\beta_i$ coefficient with respect to the IDM, the rate for Higgs-mediated processes (63) will change by $\beta_i^2$. If we are to consider an IDM-like case with $\beta_{2,3} \ll \beta_1$ then we could expect to reproduce results for the IDM. However, the interference between diagrams may be in principle important, and as our analysis shows,
they do influence the results. Notice also, that since CP symmetry is not preserved in this model, additional channels like $HH \rightarrow h_i \rightarrow Zh_j$ can appear if DM particle is heavy enough.

### 5.1 DM constraints

Masses of inert scalars and the DM candidate are constrained in cIDMS, like in the IDM, by various experimental limits. Collider constraints for inert particles were discussed in section 3.7 below we present results and limits from the dedicated dark matter experiments.

1. We expect the relic density of $H$ to be in agreement with Planck data [30]:

$$\Omega_{DM}h^2 = 0.1199 \pm 0.0027,$$

which leads to the $3\sigma$ bound:

$$0.1118 < \Omega_{DM}h^2 < 0.128.$$ (68)

If a DM candidate fulfills this requirement, then it constitutes 100% of dark matter in the Universe. A DM candidate with $\Omega_{DM}h^2$ smaller than the observed value is allowed, however in this case one needs to extend the model to have more DM candidates to complement the missing relic density. Regions of the parameter space corresponding to the value of $\Omega_{DM}h^2$ larger than the Planck upper limit are excluded. In this work calculation of $\Omega_{DM}h^2$ was performed with an aid of micrOMEGAs 3.5 [31]. In these calculations all (co)annihilation channels are included, with states with up to two virtual gauge bosons allowed.

2. The strongest constraints for light DM annihilating into $bb$ or $\tau \tau$ from indirect detection experiments are provided by the measurements of the gamma-ray flux from Dwarf Spheroidal Galaxies by the Fermi-LAT satellite, ruling out the canonical cross-section $\langle \sigma v \rangle \approx 3 \times 10^{-26}$ cm$^3$/s for $M_{DM} \lesssim 25-40$ GeV [32, 33]. For the heavier DM candidates
PAMELA and Fermi-LAT experiments provide similar limits of $\langle \sigma v \rangle \approx 10^{-25}$ cm$^3$/s for $M_{DM} = 200$ GeV in the $b\bar{b}, \tau\tau$ or $WW$ channels [34]. H.E.S.S. measurements of signal coming from the Galactic Centre set limits of $\langle \sigma v \rangle \approx 10^{-25} - 10^{-24}$ cm$^3$/s for masses up to TeV scale [35].

3. Current strongest upper limit on the spin independent (SI) scattering cross section of DM particles on nuclei $\sigma_{DM-N}$ is provided by the LUX experiment [36]:

$$\sigma_{DM-N} < 7.6 \times 10^{-46} \text{ cm}^2 \text{ for } M_{DM} = 33 \text{ GeV}. \quad (69)$$

### 5.2 Benchmarks

In this section we discuss properties of DM for chosen benchmarks in agreement with constraints from LHC/LEP:

- **A1**: $M_{h_1} = 124.83$ GeV, $M_{h_2} = 194.46$ GeV, $M_{h_3} = 239.99$ GeV,

- **A2**: $M_{h_1} = 124.85$ GeV, $M_{h_2} = 288.16$ GeV, $M_{h_3} = 572.25$ GeV,

- **A3**: $M_{h_1} = 125.01$ GeV, $M_{h_2} = 301.41$ GeV, $M_{h_3} = 1344.01$ GeV,

- **A4**: $M_{h_1} = 125.36$ GeV, $M_{h_2} = 149.89$ GeV, $M_{h_3} = 473.95$ GeV.

By choosing values of $M_{h_1,h_2,h_3}$ we determine parameters from the Higgs sector: $\lambda_1, \lambda_{s1}, \Lambda_1, \rho_2, \rho_3, \xi$, as discussed in sec.3.6 Corresponding values of parameters of the potential for each benchmark are presented in Appendix C.

Above values were chosen to illustrate different possible scenarios:

- For A1 all Higgs particles are relatively light, although only one, the SM-like Higgs $h_1$, is lighter than $2M_W$.

- Cases A2 and A3 are similar to A1; the important difference is the value of $M_{h_3}$, which is of the order of 500 GeV or 1 TeV, respectively.
In scenario A4 there are two Higgs particles that have mass below $2M_W$: $h_1$ (the SM-like Higgs) and $h_2$.

We treat $2M_W$ as the distinguishing value because two Higgs particles of masses smaller than $2M_W$ influence the DM phenomenology by introducing another resonance region in the medium DM mass regime.

Below we shall discuss properties of DM for the listed benchmark points. In this paper we focus on three different mass regions:

1. light DM mass: $50 \text{ GeV} < M_H < M_{h_1}/2$ with $M_A = M_H + 50 \text{ GeV}, M_{H^\pm} = M_H + 55 \text{ GeV},$

2. medium DM mass: $M_{h_1}/2 < M_H < M_W$ with $M_A = M_H + 50 \text{ GeV}, M_{H^\pm} = M_H + 55 \text{ GeV},$

3. heavy DM mass: $M_H \gtrsim 500 \text{ GeV}$ with $M_A = M_{H^\pm} = M_H + 1 \text{ GeV},$

which are based on studies of the IDM. Those mass splittings are in agreement with all collider constraints, including the EWPT limits, for all studied benchmark points (see Table 2 in Appendix D for exact values).

We are not going to address the possibility of accidental cancellations in region $M_W < M_H < 160 - 200 \text{ GeV}$ [28], leaving it for the future work. Note however, that this region could in principle be modified with respect to the IDM in benchmarks A2 and A3.

### 5.3 Light DM

In this work we define the light DM region as $50 \text{ GeV} < M_H < 62 \text{ GeV}$. As mentioned in section 3.7 and 4, the SM-like Higgs particle can decay invisibly into a $HH$ pair (or also

\footnote{Very light DM particle from the IDM with $M_H \lesssim 10 \text{ GeV}$ is excluded by combined relic density and Higgs-invisible decay limits from the LHC [8].}
into $AA$, if we allow $M_A < M_{h_1}/2$). Measurements of invisible decays constrain strongly the value of the DM-Higgs coupling, which in case of cIDMS is $c_1c_2\lambda_{345}$.

Results presented in this section were obtained for benchmark A1. Other benchmarks were also tested and they provide no noticeable change in the results. In all considered benchmarks $c_1c_2 \approx 1$ and the main annihilation channel of DM particles is $HH \rightarrow h_1 \rightarrow b\bar{b}$, regardless of the values of $M_{h_2}$ and $M_{h_3}$.

In the Fig. 15 relation between $\Omega_{DM}h^2$ and $M_H$ is presented, for a few chosen values of $\lambda_{345}$. As discussed before, $\lambda_{345} \sim 0.015 - 0.02$ is the boundary value which is in agreement with LHC limits for $Br(h \rightarrow inv)$. From plot 15 one can see that this value gives proper relic density for masses of the order of 53 GeV, which is a that had been previously obtained for One- and Two-Inert Doublet Models [8, 22]. This value of coupling for masses below 53 GeV results in relic density well above the Planck limits, which leads to the overclosing of the Universe. For those smaller masses, to obtain a proper relic density, one needs to enhance the DM annihilation by taking a bigger value of coupling ($\lambda_{345} \sim 0.05, 0.07$), which at the same time will lead to the enhanced Higgs invisible decays and this is not in agreement with the LHC results. For masses bigger than 53 GeV coupling corresponding to the proper relic abundance gets smaller ($\lambda_{345} \sim 0.002$), fitting into LHC constraints.

As discussed in section 4 if the Higgs can decay invisibly, its total decay width is strongly affected with respect to the SM, and therefore it is not possible to obtain enhancement in the Higgs di-photon decay channel, i.e. $R_{\gamma\gamma} < 1$, see Fig. 11. This was confirmed by the direct check we performed, and the detailed values are presented in the Appendix D in Table 3. Maximum allowed value of $R_{\gamma\gamma}$ for parameters which are in agreement both with the relic density constraints, and with the LHC invisible branching ratio limits, is between $R_{\gamma\gamma} \approx 0.85 - 0.91$ for benchmarks A1-A3. It is interesting to note, that for benchmark A4, i.e. the one with two relatively light Higgs particles, results are different – $R_{\gamma\gamma}$ differs from
the SM value for more than 20%. This is an important difference, because for light DM particles calculation of relic density does not depend on the chosen benchmark.

Similar situation happens with values of $\mathcal{R}_{Z\gamma}$, which are close to the SM value for benchmarks A1-A3 (depending on the values of parameters one can obtain both an enhancement and a suppression with respect to $\mathcal{R}_{Z\gamma} = 1$), however for benchmark A4 this channel is suppressed by more than 20%.

![Graph](image)

**Figure 15:** Values of DM relic density ($\Omega_{DM}h^2$) with respect to DM mass ($M_H$) for chosen values of $\lambda_{345}$ parameter, for benchmark A1. Horizontal lines represent 3σ Planck bounds, region above is excluded, in region below additional DM candidate is needed to complement missing DM relic density. Calculations done for $M_A = M_H + 50$ GeV, $M_{H\pm} = M_H + 55$ GeV, however exact values of those parameters do not influence the output, as the coannihilation effects are suppressed.

### 5.4 Medium DM

In this section we focus on the medium mass region from the IDM, i.e. masses of DM candidate between $M_{h1}/2 \approx 62$ GeV and $M_W \approx 83$ GeV.

Figures 16 show the behaviour of relic density with respect to $\lambda_{345}$ for masses of dark matter candidate changing between $M_{h1}/2$ and $M_W$, for chosen cIDMS benchmark points A1-A3 (Fig. 16a) and A4 (Fig. 16b). Results for the IDM are well known in the literature and this case is added for comparison in Fig. 16c. There is a near-resonance region, $M_H \sim M_{h1}/2$, symmetric around $\lambda_{345} \approx 0$. Larger DM mass corresponds to the greater significance of
annihilation into gauge bosons, causing the asymmetry with respect to $\lambda_{345} = 0$. Also, the increased annihilation rate leads to the lowered relic density.

This behaviour is repeated by benchmark points A1-A3 of cIDMS, where both additional Higgs particles are heavier than $2M_W$. However, one can see that the presence of those additional states is non-negligible. It is important to stress that even for $\beta_{2,3} \ll \beta_1$, i.e. the case that was supposed to be close to the IDM, the impact of three Higgs states on the value of relic density is significant. Annihilation channel (63) gives

$$\sigma(HH \rightarrow \bar{f}f)_{cIDMS} = \sigma(HH \rightarrow \bar{f}f)_{IDM} + \sigma_{\text{int}}. \quad (74)$$

In general, annihilation of DM particles is enhanced and therefore the relic density for a given mass is lower than the one corresponding to DM candidate from the IDM. It means, that in the cIDMS for the masses of DM candidate bigger than 79 GeV relic density is below Planck limit, while for the IDM masses up to 83 GeV can be in agreement with the measured value.

A new phenomena with respect to the IDM can happen if one of the extra Higgs bosons is lighter than $2M_W$, which is the case for benchmark A4. As the mass of DM candidate gets closer to this $h_2$-resonance, i.e. $M_{DM} \gtrsim 70$ GeV, the effective annihilation cross-section increases, resulting in the relic density below the observed value. Clearly, the annihilation rate is enhanced and dominated by the Higgs-type exchange through $h_2$ (note the symmetric distribution around $\lambda_{345} = 0$), in contrast to the previously discussed cases, whereas for the heavier masses the annihilation into gauge bosons is starting to dominate, therefore pushing the good region towards negative values of $\lambda_{345}$. 
Figure 16: Relation between DM relic density $\Omega_{DM}h^2$ and $\lambda_{345}$ for chosen values of $M_H$ for (a) benchmark A2, (b) benchmark A4, (c) the IDM. Horizontal lines represent Planck limits for $\Omega_{DM}h^2 = 0.1199 \pm 3\sigma$, region above is excluded. Calculations done for $M_A = M_H + 50\text{ GeV}, M_{H^\pm} = M_H + 55\text{ GeV}$, however exact values of those parameters do not influence the output, as the coannihilation effects are surpressed.

The difference between benchmarks is even more striking if one studies good regions of relic density in plane $(M_H, \lambda_{345})$, as presented in Fig. 17. For cases A1-A3 the behaviour follows the one from the IDM, with corresponding couplings being slightly smaller. Nevertheless, the scenario is repeated and one can clearly see the shift towards the negative values of coupling. In case of benchmark A4 the situation is completely different; not only the mass range is significantly reduced with respect to the previous cases and the IDM, but also the values of coupling are much smaller, concentrated symmetrically around zero.
Figure 17: Relic density constraints on the mass of the DM candidate and its coupling to SM Higgs boson, with the white and gray regions representing too little and too much relic abundance respectively. Red and blue regions correspond to relic density in agreement with Planck measurements for benchmark A2 and A4, respectively.

The cIDMS, as other scalar DM models, can be strongly constrained by results of direct detection experiments. Current strongest limits come from LUX experiment, and are presented in Fig. 18. There are also results of calculation of DM-nucleus scattering cross-section, $\sigma_{DM,N}$ for the benchmark points discussed in this section. Red round points denote benchmarks A1-A3, while blue triangle points correspond to benchmark A4. The difference between those two groups is clear. In case of benchmark A4, the coupling is usually much smaller than in cases A1-A3, therefore the resulting cross-section will be also smaller\(^6\) falling well below the current experimental limits.

\(^6\)Recall that the DM scattering off nuclei is mediated by the Higgs particles, $h_1, h_2, h_3$, therefore the strength of this scattering will directly depend on the value of DM-Higgs couplings.
Figure 18: Direct detection constraints for considered benchmarks (A1-A3: red points, A4: blue triangles). All points are in agreement with relic density measurements and collider constraints. Black line: upper LUX limit.

LHC analysis provides us with further constraints for the studied region. For benchmarks A1-A4 values of $R_{\gamma\gamma}$ and $R_{Z\gamma}$ are within the ATLAS & CMS experimental errors, although the preferred value of $R_{\gamma\gamma}$ and $R_{Z\gamma}$ is below 1. The value of these signal strengths depends on the exact values of parameters and an enhancement is possible, but not automatic. All values are listed in Table 4 in Appendix D.

Case A4 differs from the other three benchmarks because of the presence of an extra light Higgs particle. For points that have good relic density, allowed values of $R_{\gamma\gamma}$ are close to $R_{\gamma\gamma} \approx 0.75$, with $R_{Z\gamma}$ also below 1, namely $R_{Z\gamma} \sim 0.79$ (see the Table 4 in Appendix D).

Recall however, that in contrast with the low DM mass region, here difference between two groups of benchmarks is visible already during calculations of DM relic density.
5.5 Heavy DM

In the heavy mass regime all inert particles have similar masses, because of perturbativity limits for self-couplings $\lambda_i$. Those masses are driven by the value of $m_{22}^2$, which can reach large negative values. Therefore, the mass splittings given by combination of $\lambda_{4,5}$ are small. In this analysis we choose them to be:

$$M_A = M_{H^\pm} = M_H + 1 \text{ GeV}.$$  \hspace{1cm} (75)

Fig. 19 presents the relation between relic density $\Omega_{DM} h^2$ and DM-Higgs coupling $\lambda_{345}$ for benchmarks A1 and A3, for fixed values of DM mass. Difference between A1 and A3 lies in the fact that for benchmark A3 there is one very heavy Higgs particle. Note however, that the obtained results are very similar, and a very small difference is visible only for masses $M_H \sim 625 - 650 \text{ GeV} \sim M_{h_a}/2$. For heavy masses the 4-vertex annihilation and coannihilation channels into gauge bosons dominate the annihilation cross-section, therefore the contribution from additional Higgs states is not nearly as relevant as it was for the medium mass region. Therefore we conclude that the presence of heavy Higgs particles of different masses does not differentiate between the cases.

Figure 19: Heavy DM candidate: relation between relic density and DM-Higgs coupling $\lambda_{345}$ for benchmarks A1 (dashed lines) and A3 (solid lines) for chosen values of $M_H$. Results for A2 and A4 are equivalent to A1. Horizontal lines denote 3$\sigma$ Planck limits.
It is interesting to note, that this region of masses is more similar to the low DM mass region, that to the medium mass region. Although all benchmarks result in the very similar values of $\Omega_{DM}h^2$, just like for the light DM, there is a difference when it comes to $R_{\gamma\gamma}$ and $R_{Z\gamma}$. Again, for cases A1-A3 the preferred value of $R_{\gamma\gamma}$ is bigger, this time tending towards the close neighbourhood of 1. For case A4 resulting values are smaller, of the order of 0.8. Detailed values are presented in Table 5 in Appendix D.

6 Conclusions and Outlook

In this work we have studied the cIDMS – an extension of the Standard Model, namely a $Z_2$ symmetric Two-Higgs Doublet Model with a complex singlet. This model, apart from having a $Z_2$-odd scalar doublet, which may provide a good DM candidate, contains a complex singlet with a non-zero complex VEV, which can bring additional sources of CP violation. This is a feature that is missing from the IDM.

Within the model different scenarios can be realized. We have focused on the case where the SM-like Higgs particle, existence of which has been confirmed by the ATLAS and CMS experiments at the LHC, comes predominantly from the first, SM-like doublet, with a small modification coming from the singlet. In addition to the SM-like Higgs there are two other Higgs particles, and their presence can influence Higgs and DM phenomenology strongly.

We constrain our model by comparing the properties of the light Higgs particle ($h_1$) from the cIDMS with the one arising from the SM. LHC results provide limits for the Higgs-decay signal strengths, in particular $h_1 \rightarrow \gamma\gamma$. There are correlations $R_{\gamma\gamma} \sim R_{Z\gamma}$ and $R_{\gamma\gamma} \sim R_{ZZ}$. Maximum value for $h_1 \rightarrow ZZ$ signal strength is 1. For smaller masses of the charged scalar there is a possibility of enhancement of both $R_{\gamma\gamma}$ and $R_{Z\gamma}$. For heavier $M_{H^\pm}$ the maximum values tend to the SM value. $R_{\gamma\gamma}$ and $R_{Z\gamma}$ can be bigger than 1 if there is a constructive
interference between the SM and the cIDMS contributions. Notice, that this enhancement is possible simultaneously as in the IDM, i.e. there is a correlation between enhancement in $\gamma\gamma$ and $Z\gamma$ channels.

The cIDMS can provide a good DM candidate, which is in agreement with the current experimental results. The low DM mass region, which we define as masses of $H$ below $M_{h_1}/2$, reproduces behaviour of known Higgs-portal DM models, like the IDM. For $M_H \lesssim 53$ GeV it is not possible to fulfil LHC constraints for the Higgs invisible decay branching ratio and relic density measurements at the same time. For $53$ GeV $\lesssim M_H \lesssim 63$ GeV we are in the resonance region of enhanced annihilation with very small coupling $\lambda_{345}$ corresponding to proper relic density. This region is in agreement with collider and DM direct detection constraints, however we expect the loop corrections to play an important role here. It is important to stress that, while DM phenomenology does not depend on the chosen benchmark point (A1-A4), there is a difference when it comes to the LHC observables. Values of $R_{\gamma\gamma}$ for benchmark A4 are smaller than in all other cases.

For heavier DM mass, the mere presence of heavier Higgs particles changes the annihilation rate of DM particles. Our studies show that the annihilation cross-section is enhances with respect to the IDM and therefore relic density in the cIDMS is usually lower than for the corresponding point in the IDM. This is the case both in medium and heavy DM mass region.

The most striking change with respect to the IDM arises in the relic density analysis with the possibility of having an additional resonance region if mass of one of additional Higgs particles is smaller than $2M_W$. For our chosen benchmark points it happens in case A4. Corresponding DM-Higgs couplings, and therefore the resulting DM-nucleus scattering-cross-section constrained by results of direct detection experiments, are much smaller for A4 than for other benchmark points. This point, however, results in the much smaller values of
$\mathcal{R}_{\gamma\gamma}$ and $\mathcal{R}_{Z\gamma}$. Those values are on the edge of 20% difference with respect to the SM value, and – while not being yet excluded by the experiments within current experimental errors, they are not favoured. For other studied benchmark points, both relic density calculations, and the LHC observables, do not depend very strongly on the exact values of masses of Higgs particles. Preferred values of $\mathcal{R}_{\gamma\gamma}$ are of the order of 0.95.

In the heavy mass region all inert particles are heavier than the particles from the SM sector and the impact on the Higgs phenomenology can be minimal. For example, this is the region where $\mathcal{R}_{\gamma\gamma}$ is the closest to the SM value.

Significant modification of our model with respect to the IDM, is the possibility of having additional source of CP violation. In a CP-conserving Higgs sector, only real components of Higgs multiplets would couple to vector boson pairs (e.g. $h_i ZZ$, $h_i W^+ W^-$). In the CP-conserving 2HDM with a real singlet model we would have two CP-conserving neutral states, $h_1, h_2$, that couple to $VV$ pair. In a CP-violating Higgs sector, as in the case of cIDMS, there is mixing between the real and imaginary parts of Higgs multiplets, resulting in all three states $h_1, h_2$ and $h_3$ coupling to $VV$ pairs. LHC constraints that make $h_1 VV$ couplings so SM-like, suggest the corresponding couplings of $h_2$ and $h_3$ would be small.

Further CP violating effects may appear in the fermionic sector, when the general Yukawa coupling is modified by the CP-violating phases. However, by construction only $\Phi_1$ couples to fermions (up-, down-type quarks and charged leptons), and such effects are not present, except maybe in the neutrino sector.

Therefore we suggest the only possible signal of CP violation would come from the scalar interactions arising from the Higgs potential, and in particular those proportional to parameters $\kappa_2$ or $\kappa_3$. It may be needed to study the triple interactions from the Higgs potential, in order to identify 3-point coupling of the type $h_i h_j h_k$, which would only appear when there is CP violation present in the model.
The purpose of this paper was to find general properties of the model, which allows for additional source of CP violation, at the same time being in agreement with all existing collider data, especially on Higgs sector, and dedicated dark matter experiments. Further investigation is needed to establish the amount of CP violation provided by the model, which is our plan for the future work.

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A Decays $h \to \gamma\gamma$ and $h \to Z\gamma$

The decay width, $\Gamma(h \to \gamma\gamma)$, in the IDMS model is given by, $^{23, 37}$,

$$\Gamma(h \to \gamma\gamma) = R_{11}^2 |1 + \eta_1|^2 \Gamma(\phi_{SM} \to Z\gamma).$$  \hfill(76)

Then the ratio $R_{\gamma\gamma}$ turns out,

$$R_{\gamma\gamma} = R_{11}^2 |1 + \eta_1|^2,$$  \hfill(77)

where

$$\eta_1 = \frac{g_{h_1 H^+H^-} v}{2 R_{11} M_{H^\pm}^2} \left( \frac{A_{H^\pm}}{A_{SM}^H + A_{SM}^W} \right).$$  \hfill(78)

The form factors for this decay are,

$$A_{H^\pm} = A_0 \left( \frac{4 M_{H^\pm}^2}{M_{h_1}^2} \right),$$

$$A_{SM}^H = \frac{4}{3} A_{1/2} \left( \frac{4 M_{h_1}^2}{M_{h_1}^2} \right),$$

$$A_{SM}^W = A_1 \left( \frac{4 M_W^2}{M_{h_1}^2} \right).$$  \hfill(79)
where,
\[
A_{1/2}(\tau) = 2\tau [1 + (1 - \tau)f(\tau)],
\]
\[
A_1(\tau) = -[2 + 3\tau + 3\tau(2 - \tau)f(\tau)],
\]
\[
A_0(\tau) = -\tau [1 - \tau f(\tau)],
\]  
(80)

and

\[
f(\tau) = \begin{cases} 
\arcsin^2(1/\sqrt{\tau}) & \text{for } \tau \geq 1 \\
-\frac{1}{4} \left( \log \frac{1 + \sqrt{1 - \tau}}{1 - \sqrt{1 - \tau}} - i\pi \right)^2 & \text{for } \tau < 1.
\end{cases}
\]  
(81)

The decay width, \(\Gamma(h \to Z\gamma)\), in the IDMS model is given by,

\[
\Gamma(h \to Z\gamma) = R_{11}^2 |1 + \eta_2|^2 \Gamma(\phi_{SM} \to Z\gamma)
\]  
(82)

and the ratio for this process turns out,

\[
\mathcal{R}_{Z\gamma} = R_{11}^2 |1 + \eta_2|^2,
\]  
(83)

where

\[
\eta_2 = \frac{g_{h1H+H-v}}{2 R_{11} M_{H^\pm}} \left( \frac{\mathcal{A}_{H^\pm}}{\mathcal{A}_{W}^{SM} + \mathcal{A}_{t}^{SM}} \right),
\]  
(84)

\[
\mathcal{A}_{H^\pm} = -\frac{(1 - 2 \sin^2 \theta_W)}{\cos \theta_W} I_1 \left( \frac{4 M_{H^\pm}^2}{M_h^2}, \frac{4 M_{H^\pm}^2}{M_Z^2} \right),
\]

\[
\mathcal{A}_{t}^{SM} = 2 \frac{(1 - \frac{8}{3} \sin^2 \theta_W)}{\cos \theta_W} A_{1/2}^h \left( \frac{4 M_t^2}{M_h^2}, \frac{4 M_t^2}{M_Z^2} \right),
\]

\[
\mathcal{A}_{W}^{SM} = A_{1/2}^h \left( \frac{4 M_W^2}{M_h^2}, \frac{4 M_W^2}{M_Z^2} \right),
\]  
(85)

\[
A_{1/2}^h(\tau, \lambda) = I_1(\tau, \lambda) - I_2(\tau, \lambda),
\]

\[
A_{t}^h(\tau, \lambda) = \cos \theta_W \left\{ 4 \left( 3 - \frac{\sin^2 \theta_W}{\cos^2 \theta_W} \right) I_2(\tau, \lambda) + \left[ \left( 1 + \frac{2}{\tau} \right) \frac{\sin^2 \theta_W}{\cos^2 \theta_W} - \left( 5 + \frac{2}{\tau} \right) \right] I_1(\tau, \lambda) \right\},
\]

\[
I_1(\tau, \lambda) = \frac{\tau \lambda}{2(\tau - \lambda)} + \frac{\tau^2 \lambda^2}{2(\tau - \lambda)^2} [f(\tau) - f(\lambda)] + \frac{\tau^2 \lambda}{(\tau - \lambda)^2} \left[ g(\tau^{-1}) - g(\lambda^{-1}) \right],
\]

\[
I_2(\tau, \lambda) = -\frac{\tau \lambda}{2(\tau - \lambda)} [f(\tau) - f(\lambda)],
\]  
(86)
and
\[ g(\tau) = \begin{cases} \sqrt{\frac{1}{\tau} - 1} \arcsin \sqrt{\tau} & \text{for } \tau \geq 1 \\ \sqrt{\frac{1 - \tau}{2}} \left( \log \frac{1 + \sqrt{1 - \tau}}{1 - \sqrt{1 - \tau}} - i\pi \right) & \text{if } \tau < 1. \end{cases} \] (87)

### B Oblique parameters

To study contributions to oblique parameters in the cIDMS we use the method presented in [20]. There are 6 neutral fields (including a Goldstone boson), related to the physical fields \( h_{1-3}, H, A \) through:

\[
\begin{pmatrix}
\varphi_1 + iG^0 \\
H + iA \\
\varphi_2 + i\varphi_3
\end{pmatrix} = V
\begin{pmatrix}
G^0 \\
h_1 \\
H \\
A \\
h_2 \\
h_3
\end{pmatrix},
\] (88)

The \( 3 \times 6 \) rotation matrix \( V \) is given by

\[
V = \begin{pmatrix}
i & R_{11} & 0 & 0 & R_{21} & R_{31} \\
0 & 0 & 1 & i & 0 & 0 \\
0 & R_{12} + iR_{13} & 0 & 0 & R_{22} + iR_{23} & R_{32} + iR_{33}
\end{pmatrix},
\] (89)

where \( R_{ij} \) are the elements of the inverse rotation matrix defined in section 3.5.

Charged sector contains only a pair of charged scalars \( H^\pm \) from doublet \( \Phi_2 \).

\( S \) and \( T \) parameters in the cIDMS are given by:
The function is given by

\[
T = \frac{g^2}{64\pi^2 M_W^2 \alpha_{ew}} \left\{ F(M_{H^\pm}^2, M_1^2) + F(M_{H^\pm}^2, M_2^2) - F(M_H^2, M_2^2) \\
-(R_{12}R_{23} - R_{13}R_{22})^2 F(M_{h_1}^2, M_{h_2}^2) \\
-(R_{12}R_{33} - R_{13}R_{32})^2 F(M_{h_1}^2, M_{h_3}^2) - (R_{22}R_{33} - R_{32}R_{32})^2 F(M_{h_1}^2, M_{h_2}^2) \\
+3(R_{11})^2 (F(M_Z^2, M_{h_1}^2) + F(M_Z^2, M_{h_3}^2)) - 3(F(M_Z^2, M_{h_{ref}}^2) - F(M_W^2, M_{h_{ref}}^2)) \\
+3(R_{21})^2 (F(M_Z^2, M_{h_3}^2) - F(M_W^2, M_{h_2}^2)) + 3(R_{31})^2 (F(M_Z^2, M_{h_2}^2) - F(M_W^2, M_{h_3}^2)) \right\}
\]

and

\[
S = \frac{g^2}{384\pi^2 C_w^2} \left\{ (2s_w^2 - 1)^2 G(M_{H^\pm}^2, M_1^2, M_2^2) + G(M_{H^\pm}^2, M_2^2, M_Z^2) \\
+(R_{12}R_{23} - R_{13}R_{22})^2 G(M_{h_1}^2, M_{h_2}^2, M_Z^2) + (R_{12}R_{13} - R_{13}R_{32})^2 G(M_{h_1}^2, M_{h_3}^2, M_Z^2) \\
+(R_{22}R_{33} - R_{32}R_{31})^2 G(M_{h_2}^2, M_{h_3}^2, M_Z^2) + (R_{11})^2 \tilde{G}(M_{h_1}^2, M_Z^2) \\
\quad - \tilde{G}(M_{h_{ref}}^2, M_Z^2) + (R_{21})^2 \tilde{G}(M_{h_2}^2, M_Z^2) + (R_{31})^2 \tilde{G}(M_{h_3}^2, M_Z^2) - 2\log(M_{H^\pm}^2) + \log(M_3^2) + \log(M_2^2) + \log(M_1^2) - \log(M_{h_{ref}}^2)^2 + \log(M_{h_2}^2) + \log(M_{h_3}^2) \right\},
\]

where used functions are defined as:

\[
F(M_1^2, M_2^2) = \frac{1}{2} (M_1^2 + M_2^2) - \frac{M_2^2 M_3^2}{M_1^2 - M_2^2} \log(M_1^2 / M_2^2),
\]

\[
G(m_1, m_2, m_3) = -\frac{16}{3} + \frac{5(m_1 + m_2)}{m_3} - \frac{2(m_1 - m_2)^2}{m_3^2} \\
+ \frac{3}{m_3} \left[ \frac{m_1^2 + m_2^2}{m_1 - m_2} - \frac{m_1^2 - m_2^2}{m_3} + \frac{(m_1 - m_2)^3}{3m_3^2} \right] \log \frac{m_1}{m_2} + \frac{f(t, r)}{m_3^3},
\]

The function \( f \) of

\[
t \equiv m_1 + m_2 - m_3 \quad \text{and} \quad r \equiv m_3^2 - 2m_3(m_1 + m_2) + (m_1 - m_2)^2
\]

is given by

\[
f(t, r) = \begin{cases} 
\sqrt{r} \ln \left[ \frac{\sqrt{r}}{t + \sqrt{r}} \right], & r > 0, \\
0, & r = 0, \\
2\sqrt{-r} \arctan \frac{\sqrt{-r}}{r}, & r < 0,
\end{cases}
\]
and
\[
\tilde{G}(m_1, m_2) = -\frac{79}{3} + 9 \frac{m_1}{m_2} - 2 \frac{m_1^2}{m_2^2} \\
+ \left( -10 + 18 \frac{m_1}{m_2} - 6 \frac{m_1^2}{m_2^2} + \frac{m_1^3}{m_2^3} - 9 \frac{m_1 + m_2}{m_1 - m_2} \right) \log \frac{m_1}{m_2}.
\]

(96)

C Benchmarks

Based on analysis done in section 3.6 we propose four benchmark points to be used in DM analysis. Chosen values of masses of Higgs particles and corresponding parameters are listed in Table 1. We also present rotation matrices $R_{Ai}$ for each benchmark. These matrices diagonalize the scalar mass matrix, $M^2_{\text{mix}}$ in the following way,

\[
\tilde{M}^2 = R_{Ai} M^2_{\text{mix}} R^T_{Ai} = \text{diag}(M^2_{h_1}, M^2_{h_2}, M^2_{h_3}).
\]

(97)

|       | $M_{h_1}$ | $M_{h_2}$ | $M_{h_3}$ |
|-------|-----------|-----------|-----------|
| A1)   | 124.838   | 194.459   | 239.994   |
| A2)   | 124.852   | 288.161   | 572.235   |
| A3)   | 125.011   | 301.407   | 1344.01   |
| A4)   | 125.364   | 149.889   | 473.953   |

|       | $\lambda_1$ | $\lambda_{s1}$ | $\Lambda_1$ | $\rho_2$ | $\rho_3$ | $\xi$ |
|-------|--------------|-----------------|-------------|---------|---------|-------|
| A1)   | 0.2579       | 0.2241          | -0.0100     | 0.0881  | 0.1835  | 1.4681 |
| A2)   | 0.2869       | 0.8894          | -0.1563     | 0.6892  | 0.6617  | 0.8997 |
| A3)   | 0.2816       | 0.8423          | -0.1391     | 0.7010  | -0.5150 | 1.4758 |
| A4)   | 0.2830       | 0.6990          | 0.0928      | 0.3478  | 0.2900  | 0.4266 |

Table 1: In the first subtable we show the masses of the scalars in GeV. In the second the values of Higgs sector dimensionless parameters which are involved in the scalar potential are listed.

\(^7\)In tables in appendices C and D we are listing parameters with a larger precision to allow the reader to reproduce our results.
\( R_{A1} = \begin{pmatrix} 0.999465 & 0.00682726 & 0.0319988 \\ -0.0324672 & 0.328031 & 0.944109 \\ -0.0040509 & -0.944642 & 0.328077 \end{pmatrix} \). \hfill (98)

\( R_{A2} = \begin{pmatrix} 0.987153 & 0.0555822 & 0.149795 \\ -0.159095 & 0.255572 & 0.95361 \\ 0.0147203 & -0.965191 & 0.261131 \end{pmatrix} \). \hfill (99)

\( R_{A3} = \begin{pmatrix} 0.990547 & 0.0252929 & 0.134822 \\ -0.137173 & 0.186514 & 0.972829 \\ -0.000540612 & -0.982127 & 0.188221 \end{pmatrix} \). \hfill (100)

\( R_{A4} = \begin{pmatrix} 0.90504 & -0.0113276 & -0.425176 \\ 0.424229 & -0.0477451 & 0.904295 \\ -0.0305436 & -0.998795 & -0.0384057 \end{pmatrix} \). \hfill (101)

### D Values of \( S, T \) and \( R_{\gamma \gamma}, R_{Z\gamma} \) for studied cases

Table 2 presents values of oblique parameters \( S \) and \( T \) for chosen values of masses studied in the paper. 3\( \sigma \) bounds are:

\[-0.28 < S < 0.38, \quad -0.30 < T < 0.48, \quad -0.32 < U < 0.34.\]

Table 3, 4 and 5 contain values of \( R_{\gamma \gamma} \) and \( R_{Z\gamma} \) for different values of DM mass, for benchmarks A1-A4. All those points are in agreement with collider and DM constraints.

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[2] CMS Collaboration, *Phys. Lett.* **B716** (2012) 30.
Table 2: Values of oblique parameters $S$ and $T$ for benchmark points $A1 - A4$ and chosen masses of inert scalars. All studied cases are in agreement with EWPT constraints.

|     | $M_{h_1}$ | $M_{h_2}$ | $M_{h_3}$ | $\delta_A$ | $\delta_{\pm}$ | $M_H$ | $S$    | $T$    | $3\sigma$ |
|-----|-----------|-----------|-----------|-------------|---------------|-------|--------|--------|-----------|
| **A1)** | 124.838   | 194.459   | 239.994   | 50          | 55            | 50    | 0.0025 | 0.0050 | Yes       |
|      |           |           |           | 50          | 55            | 75    | 0.0024 | 0.0051 | Yes       |
|      |           |           |           | 1           | 1+\epsilon   | 600   | -0.0078| 0.0000 | Yes       |
| **A2)** | 124.852   | 288.161   | 572.235   | 50          | 55            | 50    | 0.0029 | -0.0378| Yes       |
|      |           |           |           | 50          | 55            | 75    | 0.0028 | -0.0377| Yes       |
|      |           |           |           | 1           | 1+\epsilon   | 600   | -0.0075| -0.0418| Yes       |
| **A3)** | 125.011   | 301.407   | 1344.01   | 50          | 55            | 50    | 0.0031 | -0.2177| Yes       |
|      |           |           |           | 50          | 55            | 75    | 0.0030 | -0.2176| Yes       |
|      |           |           |           | 1           | 1+\epsilon   | 600   | -0.0072| -0.2228| Yes       |
| **A4)** | 125.364   | 149.889   | 473.953   | 50          | 55            | 50    | 0.0027 | -0.1968| Yes       |
|      |           |           |           | 50          | 55            | 75    | 0.0026 | -0.1967| Yes       |
|      |           |           |           | 1           | 1+\epsilon   | 600   | -0.0077| -0.2019| Yes       |

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Table 3: Low DM mass region: values of $R_{\gamma\gamma}$ and $R_{Z\gamma}$ for chosen values of $M_H$ and $\lambda_{345}$ for $M_A = M_H + 50$ GeV, $M_{H\pm} = M_H + 55$ GeV. Points listed above correspond to DM relic density in agreement with Planck results. Values of $R_{\gamma\gamma}$ and $R_{Z\gamma}$ do not depend on the sign of $\lambda_{345}$.
Table 4: Medium DM mass region: values of $R_{\gamma\gamma}$ and $R_{Z\gamma}$ for chosen values of $M_H$ and $\lambda_{345}$ for $M_A = M_H + 50\,\text{GeV}$, $M_{H^\pm} = M_H + 55\,\text{GeV}$. Points listed above correspond to DM relic density in agreement with Planck results.
### Benchmark A1

| $M_H$ (GeV) | $\lambda_{345}$ | $\mathcal{R}_{\gamma\gamma}$ | $\mathcal{R}_{Z\gamma}$ |
|-------------|-----------------|-----------------|-----------------|
| 550         | 0               | 0.9986          | 0.9989          |
| 575         | 0.2             | 0.9967          | 0.9981          |
| 575         | -0.2            | 1.0005          | 0.9995          |
| 600         | 0.23            | 0.9966          | 0.9981          |
| 600         | -0.23           | 1.0006          | 0.9995          |
| 625         | 0.25            | 0.9966          | 0.9981          |
| 625         | -0.25           | 1.0006          | 0.9995          |
| 650         | 0.28            | 0.9966          | 0.9980          |
| 650         | -0.28           | 1.0007          | 0.9996          |
| 675         | 0.3             | 0.9966          | 0.9981          |
| 675         | -0.3            | 1.0007          | 0.9996          |
| 700         | 0.33            | 0.9965          | 0.9980          |
| 700         | -0.33           | 1.0007          | 0.9996          |

### Benchmark A2

| $M_H$ (GeV) | $\lambda_{345}$ | $\mathcal{R}_{\gamma\gamma}$ | $\mathcal{R}_{Z\gamma}$ |
|-------------|-----------------|-----------------|-----------------|
| 550         | 0               | 0.9741          | 0.9743          |
| 575         | 0.2             | 0.9723          | 0.9737          |
| 575         | -0.2            | 0.9760          | 0.9750          |
| 600         | 0.23            | 0.9722          | 0.9736          |
| 600         | -0.23           | 0.9761          | 0.9751          |
| 625         | 0.25            | 0.9722          | 0.9736          |
| 625         | -0.25           | 0.9761          | 0.9751          |
| 650         | 0.28            | 0.9722          | 0.9736          |
| 650         | -0.28           | 0.9762          | 0.9751          |
| 675         | 0.3             | 0.9722          | 0.9736          |
| 675         | -0.3            | 0.9762          | 0.9751          |
| 700         | 0.33            | 0.9721          | 0.9736          |
| 700         | -0.33           | 0.9762          | 0.9751          |

### Benchmark A3

| $M_H$ (GeV) | $\lambda_{345}$ | $\mathcal{R}_{\gamma\gamma}$ | $\mathcal{R}_{Z\gamma}$ |
|-------------|-----------------|-----------------|-----------------|
| 550         | 0               | 0.9808          | 0.9810          |
| 575         | 0.2             | 0.978982        | 0.9804          |
| 575         | -0.2            | 0.9827          | 0.9817          |
| 600         | 0.23            | 0.9789          | 0.9803          |
| 600         | -0.23           | 0.9828          | 0.9818          |
| 625         | 0.25            | 0.9789          | 0.9803          |
| 625         | -0.25           | 0.9828          | 0.9818          |
| 650         | 0.28            | 0.9788          | 0.9803          |
| 650         | -0.28           | 0.9829          | 0.9818          |
| 675         | 0.3             | 0.9789          | 0.9803          |
| 675         | -0.3            | 0.9829          | 0.9818          |
| 700         | 0.33            | 0.9788          | 0.9803          |
| 700         | -0.33           | 0.9830          | 0.9818          |

### Benchmark A4

| $M_H$ (GeV) | $\lambda_{345}$ | $\mathcal{R}_{\gamma\gamma}$ | $\mathcal{R}_{Z\gamma}$ |
|-------------|-----------------|-----------------|-----------------|
| 550         | 0               | 0.8188          | 0.8190          |
| 575         | 0.2             | 0.8173          | 0.8184          |
| 575         | -0.2            | 0.8203          | 0.8196          |
| 600         | 0.23            | 0.8172          | 0.8184          |
| 600         | -0.23           | 0.8204          | 0.8196          |
| 625         | 0.25            | 0.8172          | 0.8184          |
| 625         | -0.25           | 0.8205          | 0.8196          |
| 650         | 0.28            | 0.8172          | 0.8184          |
| 650         | -0.28           | 0.8205          | 0.8196          |
| 675         | 0.3             | 0.8172          | 0.8184          |
| 675         | -0.3            | 0.8205          | 0.8196          |
| 700         | 0.33            | 0.81714         | 0.8196          |
| 700         | -0.33           | 0.82057         | 0.81964         |

Table 5: Heavy DM mass region: values of $\mathcal{R}_{\gamma\gamma}$ and $\mathcal{R}_{Z\gamma}$ for chosen values of $M_H$ and $\lambda_{345}$ for $M_A = M_{H^\pm} = M_H + 1$ GeV. Points listed above correspond to DM relic density in agreement with Planck results.
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