Prepared for submission to JHEP LU-TP 13-12

Higgs properties in a softly broken Inert Doublet Model

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Abstract: We consider a model for the Higgs sector with two scalar doublets and a softly broken $\mathbb{Z}_2$ symmetry, the Stealth Doublet Model. This model can be seen as a generalization of the Inert Doublet Model. One of the doublets is the Higgs doublet that participates in electroweak symmetry breaking and couples to fermions. The other doublet does not couple to fermions at tree level and does not acquire a vacuum expectation value. The broken $\mathbb{Z}_2$ symmetry leads to interesting phenomenology such as mixing between the two doublets and charged and CP-odd scalars that can be light and have unusual decay channels. We present theoretical and experimental constraints on the model and consider the recent observation of a Higgs boson at the LHC. The data on the $H \to \gamma\gamma$ channel can be naturally accommodated in the model, with either the lightest or the heaviest CP-even scalar playing the role of the observed particle.

1 Introduction

The ATLAS [1] and CMS [2] experiments at the Large Hadron Collider (LHC) have discovered a new particle that exhibits all the features of a Higgs boson (for the most recent data see e.g. [3–5]). It will require hard work to uncover if this is the Standard Model (SM) Higgs boson or not, but the data seem to be compatible with the SM. If it is a Higgs boson, but not the one predicted by the SM, then there is likely an extended Higgs sector with additional Higgs bosons.

Arguably, the most "standard" Higgs scenarios beyond the SM are the minimal supersymmetric Standard Model (MSSM), general two-Higgs doublet models (2HDM), or perhaps the next-to-minimal supersymmetric standard model (NMSSM); see in particular ref. [6] for a recent review of 2HDMs. These models all predict a similar set of additional Higgs bosons, with associated dominating production and decay channels, and most searches are devoted to these channels.

There is a real possibility that Nature is not described by one of these standard scenarios, and if it is not, the standard searches may not be appropriate. It is therefore important to consider alternative scenarios. One such alternative is the Inert Doublet Model (IDM) [7–9], where there is a conserved $\mathbb{Z}_2$ parity, such that while one scalar plays the role of a SM-like Higgs boson, the other scalars do not couple to fermions. In particular, the lightest scalar is a stable dark matter candidate.

In this paper we present the Stealth Doublet Model (SDM), a generalization of the IDM where the $\mathbb{Z}_2$ symmetry is softly broken, and discuss its impact on Higgs physics at the LHC. In particular we study the SDM in relation to the LHC discovery and exclusion results. When the $\mathbb{Z}_2$ symmetry of the IDM is broken, the lightest scalar is not stable, and couplings of the fermiophobic particles to fermions are generated at one-loop level. The resulting phenomenology is very different from the standard scenarios discussed above, and as we will show below is also compatible with the discovered particle at LHC.

The $\mathbb{Z}_2$ symmetry is broken softly by a dimension-two term in the scalar potential. We consider this as a way to parametrize our ignorance of the symmetry breaking mechanism, in a similar way to how soft supersymmetry breaking is parametrized in e.g. the MSSM.

The particle content of the SDM is the same as in CP-conserving 2HDMs: there are two CP-even neutral scalars, h^0 and H^0, one of which should be the Higgs boson discovered at the LHC, a CP-odd neutral scalar A^0, and a charged scalar $H^\pm$. The interactions of these particles are quite different from those of 2HDMs, however.

In our model, the A^0 and $H^\pm$ have no tree-level couplings to fermions: they are *fermiophobic*. All their couplings to fermions are instead generated at the one-loop level. Their dominating production and decay modes can therefore be different than in the standard scenarios. Consequently, A^0 and $H^\pm$ can be lighter in the SDM than in standard scenarios, since flavor constraints and LEP limits do not apply. For example, if the charged scalar is the lightest scalar, its main decay is typically $H^\pm \to W^\pm\gamma$. In addition, electroweak precision tests (EWPT) allow both lighter or heavier h^0, H^0 in our model than in the SM.

In the rest of this paper we describe the SDM and its parameters, and we outline the requirements for soft symmetry breaking. We consider the various constraints on the model and the observed Higgs boson signal at LHC. Finally we briefly consider the charged scalar and its decay and production channels. We leave detailed analyses of the model for upcoming papers [10], where we will also compute all decay widths of the fermiophobic scalars and discuss LHC phenomenology in more detail. A preliminary presentation of this model can be found in [11].

2 The Stealth Doublet Model

In brief, the model consists of adding another doublet to the Standard Model scalar sector, and introducing a discrete $\mathbb{Z}_2$ parity between the two doublets. This parity is broken softly, which imposes certain relations on the parameters of the scalar potential. The scalar potential is thus the potential of two-Higgs doublet models (2HDM) with two hypercharge $Y = 1$ scalar doublet fields $\Phi_i = (\phi_i^+, \phi_i^0)^T$,

$$\begin{aligned} V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \\ &+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}, \end{aligned} \tag{2.1}$$

where we only consider CP-conserving models and therefore take all parameters to be real. The $\mathbb{Z}_2$ symmetry transformation can be taken as $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$. This parity is broken by the last three "hard-breaking" terms in eq. (2.1) and by the soft-breaking term $m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}$

Furthermore, in this model the second doublet does not get a vacuum expectation value (vev) and is therefore not really a Higgs doublet. However, because the $\mathbb{Z}_2$ symmetry is broken the two doublets can mix. Studying a model where the vev resides solely in one of the doublets is equivalent to working in the Higgs basis (see e.g. [6, 12, 13]). The Higgs basis is often useful for analyzing a general two-Higgs doublet model, but in our model, this is the physical basis, with $v = v_1 \approx 246$ GeV. Similarly to the IDM, the SDM does not have a parameter $\tan\beta = v_2/v_1$, and cannot be obtained by simply taking the limit $\tan\beta \to 0$ or $\tan\beta \to \infty$.

Minimizing the potential yields the conditions

$$m_{11}^2 = -\frac{1}{2} v^2 \lambda_1, \qquad m_{12}^2 = \frac{1}{2} v^2 \lambda_6, \tag{2.2}$$

and m_{22}^2 is thus a free parameter. Further constraints on the parameters will be discussed below.

Generally in two-Higgs doublet models where CP is conserved, there are two CP-even neutral scalars, one CP-odd neutral scalar A^0, and a charged scalar $H^\pm$. The two doublets can be written in unitary gauge as

$$\Phi_1 = \begin{pmatrix} 0 \\ \dfrac{v + \phi_1^0}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \dfrac{\phi_2^0 + \mathrm{i} A^0}{\sqrt{2}} \end{pmatrix}, \tag{2.3}$$

where $\phi_{1,2}^0$ are the neutral CP-even interaction eigenstates, whose mass matrix is not diagonal:

$$\mathcal{M}^2 = \begin{pmatrix} \lambda_1 v^2 & \lambda_6 v^2 \\ \lambda_6 v^2 & m_{22}^2 + \lambda_{345} v^2 \end{pmatrix} = \begin{pmatrix} \lambda_1 v^2 & \lambda_6 v^2 \\ \lambda_6 v^2 & m_A^2 + \lambda_5 v^2 \end{pmatrix}, \tag{2.4}$$

where $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$. The physical CP-even mass eigenstates are given by

$$H^0 = \phi_1^0 \cos\alpha + \phi_2^0 \sin\alpha \tag{2.5}$$

$$h^0 = -\phi_1^0 \sin\alpha + \phi_2^0 \cos\alpha, \tag{2.6}$$

where the mixing angle α is obtained by diagonalizing the matrix $\mathcal{M}^2$. The couplings of h^0 and H^0 to $Z^0 Z^0$ and $W^\pm W^\mp$ are thus suppressed compared to the SM Higgs by factors $\sin\alpha$ and $\cos\alpha$, respectively. Taking H^0 to be the heavier state, the masses of h^0, H^0 are

$$m_h^2 = c_\alpha^2 m_A^2 + s_\alpha^2 v^2 \lambda_1 + c_\alpha^2 v^2 \lambda_5 - 2 s_\alpha c_\alpha v^2 \lambda_6 \tag{2.7}$$

$$m_H^2 = s_\alpha^2 m_A^2 + c_\alpha^2 v^2 \lambda_1 + s_\alpha^2 v^2 \lambda_5 + 2 s_\alpha c_\alpha v^2 \lambda_6, \tag{2.8}$$

where we defined the abbreviations $s_\alpha \equiv \sin\alpha$, $c_\alpha \equiv \cos\alpha$. The masses of the remaining states are

$$m_A^2 = m_{H^\pm}^2 - \frac{1}{2} v^2 (\lambda_5 - \lambda_4) \tag{2.9}$$

$$m_{H^\pm}^2 = m_{22}^2 + \frac{1}{2} v^2 \lambda_3. \tag{2.10}$$

One may solve eqs. (2.7–2.10) for the parameters $\lambda_{1,3,4,5}$ so that the masses of the scalars can be used as model parameters. The mixing angle is given by

$$\sin 2\alpha = \frac{2 v^2 \lambda_6}{m_H^2 - m_h^2}. \tag{2.11}$$

From eqs. (2.4) and (2.11), we see that when the $\mathbb{Z}_2$ parity is exact (i.e. $\lambda_6 = 0, m_{12}^2 = 0$), there is no mixing of the CP-even states and we recover the Inert Doublet Model. In fact, all our results reduce to the IDM when letting $\lambda_6 \to 0$ and either $\sin\alpha \to 1$, $\cos\alpha \to 0$ or $\sin\alpha \to 0$, $\cos\alpha \to 1$. In this sense, our model is a generalization of the IDM.

The $\mathbb{Z}_2$ symmetry, if exact, would forbid flavor-changing neutral currents (FCNC). If the symmetry is broken, there could potentially be large FCNC. In this model the symmetry is only broken softly, i.e., the symmetry is restored at very high energies compared to the soft-breaking mass scale $|m_{12}|$, and FCNC only occur at two-loop level [10].

The requirement of soft breaking introduces additional constraints on the parameters. eq. (2.2) shows that the soft-breaking mass scale is proportional to the hard breaking coupling λ_6, so one might naively expect that if there is soft breaking, there is also hard breaking. This is not correct, however, due to the freedom to choose a basis for the doublets, i.e., to choose v_1 and v_2 [12–14]. There may exist a basis in which the hard breaking parameters $\lambda_6 = \lambda_7 = 0$ while $m_{12}^2 \neq 0$ such that the symmetry is broken softly. If this is the case, then the symmetry is broken softly in any basis.

We analyze this situation by using the methods of refs. [12–14] and find that the conditions for soft $\mathbb{Z}_2$ breaking, which hold if $\lambda_6 \neq 0$, are

$$(\lambda_1 - \lambda_2)\left[\lambda_{345}(\lambda_6+\lambda_7) - \lambda_2\lambda_6 - \lambda_1\lambda_7\right] - 2(\lambda_6-\lambda_7)(\lambda_6+\lambda_7)^2 = 0, \tag{2.12}$$

$$(\lambda_1-\lambda_2)m_{12}^2 + (\lambda_6+\lambda_7)(m_{11}^2 - m_{22}^2) \neq 0. \tag{2.13}$$

These equations imply that since the parameters are real, there exists a maximum value $\lambda_7^{\max}$ for λ_7. All couplings λ_i which fulfill eqs. (2.12, 2.13) break the $\mathbb{Z}_2$ symmetry softly. These relations are thus part of the specification of the model, and in the following we always choose parameters to respect this requirement.

The scalar potential (2.1) has ten free parameters when requiring all couplings to be real. Two are eliminated by the minimization conditions (2.2) and one by the conditions for soft breaking (2.12, 2.13). We will choose the masses of the scalar states m_h, m_H, m_A and $m_{H^\pm}$ as four of the remaining parameters. To specify the amount of $\mathbb{Z}_2$ breaking, we choose to use $\sin\alpha$, which is related to λ_6 through eq. (2.11). Two more parameters need to be specified. We take these to be λ_3 and λ_7, since λ_3 determines the coupling between h^0/H^0 and $H^\pm$. In summary, we will use as the seven parameters of the model

$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \sin\alpha,\ \lambda_3,\ \lambda_7. \tag{2.14}$$

The simplest solution to (2.12) is to choose $\lambda_7 = \lambda_6$ and $\lambda_2 = \lambda_1$. The inequality (2.13) then becomes $m_{22}^2 \neq m_{11}^2$. In our numerical calculations we will often choose λ_3 to take the values $\lambda_3 = 0$, $2m_{H^\pm}^2/v^2$ and $4m_{H^\pm}^2/v^2$, corresponding to $m_{22}^2 = m_{H^\pm}^2$, 0 and $-m_{H^\pm}^2$, respectively. We will also vary λ_3 and λ_7, within theoretically allowed regions, to deduce their impact on the signal strengths for $h^0/H^0 \to \gamma\gamma$. In ref. [10], we will study the solutions of eqs. (2.12, 2.13) in more detail.

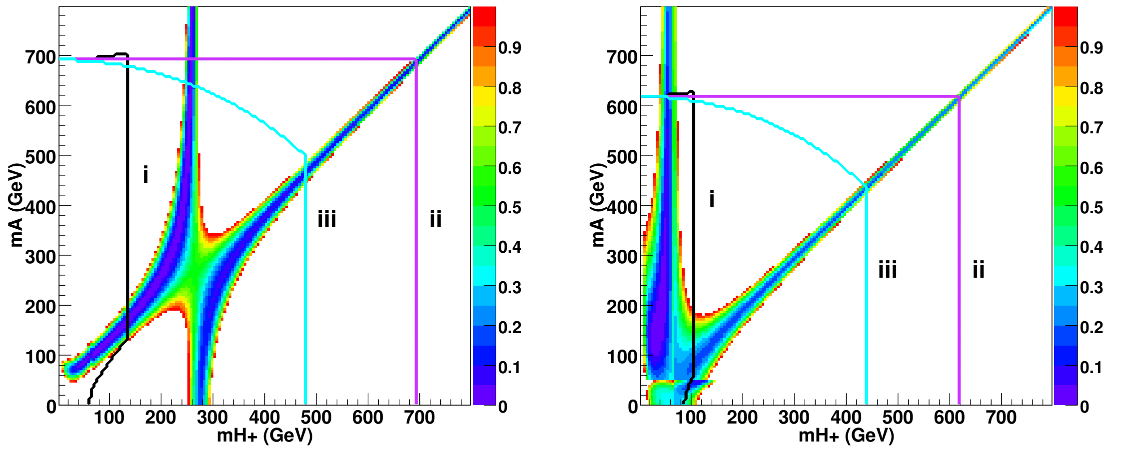
As a final step we must specify the Yukawa couplings of the model. The most general Yukawa Lagrangian in the Higgs Basis reads, in terms of the fermion flavor eigenstate [13]

$$\begin{aligned}-\mathcal{L}_{\text{Yuk}} = {} & \kappa_0^L \bar{L}_L \Phi_1 E_R + \kappa_0^U \bar{Q}_L \widetilde{\Phi}_1 U_R + \kappa_0^D \bar{Q}_L \Phi_1 D_R \\ & + \rho_0^L \bar{L}_L \Phi_2 E_R + \rho_0^U \bar{Q}_L \widetilde{\Phi}_2 U_R + \rho_0^D \bar{Q}_L \Phi_2 D_R\end{aligned} \tag{2.15}$$

where $\widetilde{\Phi}_i = -\mathrm{i}\sigma_2\Phi_i^*$. In order to obtain mass eigenstates, the matrix κ_0^F can be diagonalized by a biunitary transformation to obtain the diagonal mass matrix M^F for fermions $F = U, D, L$. The correspondingly transformed ρ^F matrix will in general be non-diagonal and will generate FCNC. To avoid FCNC at tree level, we impose positive $\mathbb{Z}_2$ parities on the fermions. This enforces $\rho^F = 0$ at tree level. The doublet Φ_2 is therefore fermiophobic, and the states $H^\pm$, A^0, and ϕ_2^0 do not interact with fermions at tree level. Fermions acquire mass through Yukawa couplings with the Higgs doublet Φ_1 only. In this sense, our model is a Type I 2HDM. The Higgs Yukawa Lagrangian is then

$$-\mathcal{L}_{\text{Yuk}} = \frac{m_f}{v}\bar{\psi}_f\psi_f\,(c_\alpha\, H - s_\alpha\, h) \tag{2.16}$$

for all fermions f. The soft breaking terms will lead to couplings between Φ_2 and fermions at one-loop level. The resulting ρ^F matrices are diagonal at one-loop level [10]. At higher



$m_h = 125$ GeV, $m_H = 300$ GeV, $s_\alpha = 0.9$.
(a)

$m_h = 75$ GeV, $m_H = 125$ GeV, $s_\alpha = 0.1$.
(b)

Figure 1. Examples of allowed regions in parameter space taking into account theoretical constraints and S and T values as a function of $m_{H^\pm}$ and m_A. The color displays the deviation from the center of the 90% C.L. ellipse of Figure 10.7 in [23], taking the value 1 if on the limiting ellipse. White regions are outside the ellipse. The regions inside the black (i) ($m_{22}^2 = m_{H^\pm}^2 \Rightarrow \lambda_3 = 0$), magenta (ii) ($m_{22}^2 = 0 \Rightarrow \lambda_3 = 2m_{H^\pm}^2/v^2$) and cyan (iii) ($m_{22}^2 = -m_{H^\pm}^2 \Rightarrow \lambda_3 = 4m_{H^\pm}^2/v^2$) lines fulfill the theoretical constraints for a given m_{22}^2 or λ_3-value. In this plot, $\lambda_2 = \lambda_1$ and $\lambda_7 = \lambda_6$.

orders, ρ^F will have off-diagonal elements and introduce FCNC, but these will be two-loop suppressed [10]. In general one could consider constraints from the renormalization group evolution of the Yukawa couplings along the lines of Ref. [15].

3 Constraints on the model

Let us now discuss the constraints that apply to the model. These are analyzed using the two-Higgs doublet model calculator 2HDMC [16, 17], where we have implemented the SDM as a new model. This makes it straightforward to obtain theoretical constraints, oblique parameters, branching ratios[1], and cross sections.

The parameters of the potential are constrained by demanding that the potential be bounded from below [7, 18] and that it respects perturbativity and tree-level unitarity[19–22]. We will refer to these conditions as "theoretical constraints." We do not list their explicit expressions here (see e.g. ref. [16]), but will take them into account in all our calculations by using 2HDMC. For details, see ref. [10].

The next set of constraints is given by electroweak precision tests (EWPT), most importantly those constraints imposed by loop contributions from the scalars to the gauge boson vacuum polarizations. Such corrections can be parametrized by the oblique parameters S, T and U [24]. These do not depend explicitly on the potential parameters, but

[1]Some of the important decay channels of $H^\pm$ and A^0 are one-loop processes that are not included in 2HDMC, and will be briefly discussed below. They will be calculated and further discussed in [10].

do so implicitly through the masses of the scalar particles in the model. All the scalars contribute to the oblique parameters, and the resulting expressions are lengthy but not particularly illuminating so we do not list them here. We use 2HDMC to evaluate them and require the obtained values of S and T to fall within the 90% C.L. ellipse in Figure 10.7 of [23].

Finally, there are constraints from collider searches at LEP, the Tevatron and the LHC. Constraints from LEP and the Tevatron and the 7 TeV LHC constraints (as implemented in the latest version of HiggsBounds, v3.8) will in the following be included through the use of the HiggsBounds program [25–27] linked to 2HDMC. These will be further discussed in the next section, but since the A^0 and $H^\pm$ in our model do not have the same interactions as in general 2HDMs, they are not much constrained by previous searches. The interactions of the CP-even scalar that has not been observed at the LHC, however, include the interactions of the SM Higgs boson, and it could therefore in principle have showed up in LHC searches.

4 Higgs and the LHC

Let us refer to the particle discovered by ATLAS and CMS as $\mathcal{H}$ and to the Higgs boson of the SM as $H_{\rm SM}$. In our model, the $\mathcal{H}$ particle with mass roughly 125 GeV can be either the lighter h^0, with a heavier H^0 remaining to be discovered, or $\mathcal{H}$ can be the heavier H^0, while the h^0 is lighter and was not discovered at LEP or the Tevatron due to small couplings. We will refer to these two cases as Case 1 and Case 2, respectively.

As we shall see below, if we want one of our CP-even scalars to account for the recent ATLAS data on the $\mathcal{H} \to \gamma\gamma$ decay channel, we must take the mixing $\sin\alpha$ relatively large in Case 1 and relatively small in Case 2. In figure 1 we therefore present examples of regions in the $(m_{H^\pm}, m_A)$-plane that are allowed by theoretical and electroweak constraints for Case 1 and Case 2. For Case 1 we choose $s_\alpha = 0.9$, and for Case 2, $s_\alpha = 0.1$. We further use $\lambda_2 = \lambda_1$ and $\lambda_7 = \lambda_6$ to satisfy eq. (2.12) in the simplest way. Note that since the S and T parameters do not explicitly depend on the λ_i, only some combinations of these parameters (i.e. the couplings and the masses of the scalars) are constrained by the electroweak precision data. We therefore additionally show in figure 1 boundaries of regions admitted by the theoretical constraints for three different values of λ_3.

From figure 1 it is clear that the masses of the scalars should not exceed roughly 700 GeV in order to fulfill the theoretical constraints. Moreover, the largest allowed region is obtained for $m_{22}^2 \approx 0$. In order to give small enough contributions to the S and T parameters, $m_{H^\pm}$ and m_A must satisfy some approximate custodial symmetries: Define $M^2 = m_H^2 \sin^2\alpha + m_h^2 \cos^2\alpha$ [28]. Then $m_A \approx m_{H^\pm} + 50$ GeV when $m_{H^\pm}^2 \lesssim M^2$ or $m_A \approx m_{H^\pm}$ when $m_{H^\pm}^2 \gtrsim M^2$ are allowed, respectively. When $m_{H^\pm}^2 \approx M^2$, then $0 \lesssim m_A \lesssim 700$ GeV is allowed. These conclusions are similar to what was found in Ref. [28].

In figure 1 we have not yet included collider constraints. Let us estimate the LHC constraints on Case 1. Then $\mathcal{H} = h^0$, while H^0 is heavier. It is constrained by the LHC searches for the SM Higgs mainly through its decays $H^0 \to ZZ^{(*)} \to 4\ell$, $H^0 \to WW^{(*)}$ and $H^0 \to \gamma\gamma$. Events where the H^0 is produced and decays in one of these channels will look

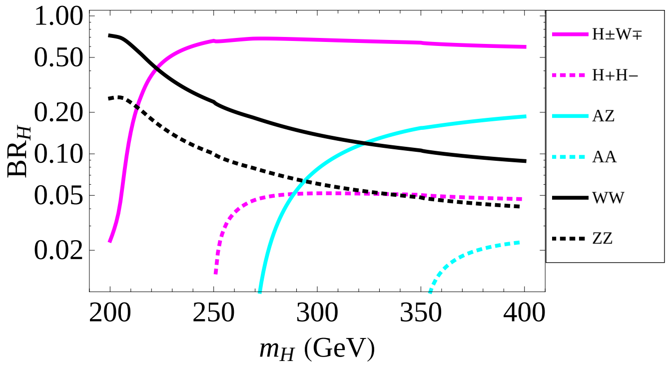
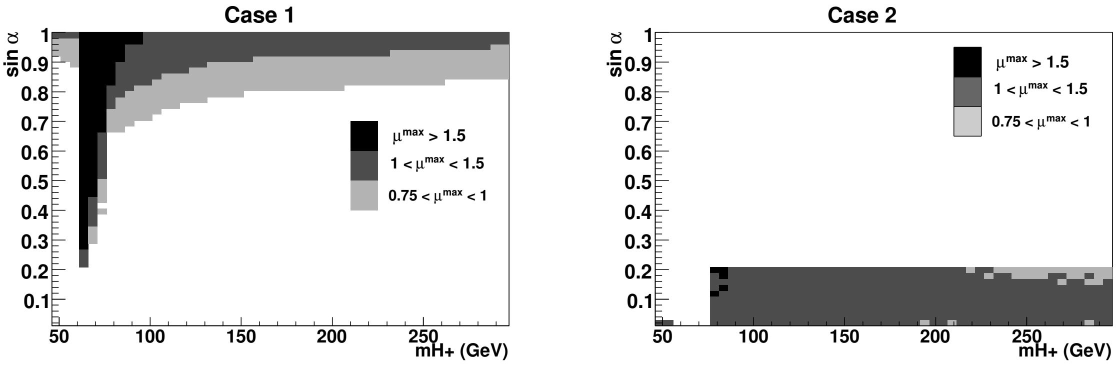


Figure 2. Branching ratios of the H^0 boson as a function of its mass. Parameter values are $m_h = 125$ GeV, $m_{H^\pm} = 125$ GeV, $m_A = 175$ GeV, $\lambda_3 = 0$, $\sin\alpha = 0.9$, $\lambda_2 = \lambda_1$ and $\lambda_7 = \lambda_6$.

exactly like the corresponding events for a SM Higgs at the same mass, so all experimental acceptances are identical. We can therefore compute the $\sigma \times$ BR for the relevant channels and use the LHC results to constrain the production of H^0.

The most sensitive exclusion is production via $gg \to H^0$ and decay via $H^0 \to ZZ$. Let us consider the most recent ATLAS exclusion in this channel shown in Figure 12a of ref. [4]. The SM curve in this plot shows $\sigma \times$ BR for $gg \to H_{\rm SM} \to ZZ \to 4\ell$. We want to rescale this curve to our model. The production processes are the same as in the SM, but the Yukawa coupling of H^0 to the heavy quark in the loop is suppressed by a factor c_α, and the same factor c_α applies to vector–boson fusion and associated production. The decay vertex $H^0 \to ZZ$ is also suppressed by the same factor c_α. However, the dominating decays to SM particles that contribute to the width Γ_{H^0} are $H^0 \to ZZ, WW, b\bar{b}, t\bar{t}$. Again, all of these processes are suppressed by the same factor c_α relative to the SM. In addition, there may be decays to the new scalars, $H^0 \to h^0h^0, H^+H^-, A^0A^0, A^0Z, H^\pm W^\mp$, if these channels are open. We may thus get a conservative upper bound on the branching ratio BR($H^0 \to ZZ$) by considering the case where none of the latter channels are open. The branching ratio is then the same as in the SM, but if any of the new channels open, it becomes smaller.

The upshot is that to obtain an absolute upper limit on $\sigma \times$ BR in our model, we need only rescale the SM result by the factor c_α^2. As an example, in figure 1a, we have chosen $s_\alpha = 0.9$, so that $c_\alpha^2 = 0.19$. Referring to the SM curve in Figure 12a of ref. [4], we see that rescaling this curve by a factor 0.19, we are below or close to the exclusion limit for all masses above 200 GeV. If we instead take $s_\alpha = 0.8$, our conservative estimate is closer to the exclusion region. Note that this is the upper limit in our model, and in most of parameter space one or more of the additional decay channels will be open, leading to a smaller BR($H^0 \to ZZ$). We conclude that at least for $s_\alpha = 0.9$ or larger, a H^0 in the mass range 200–500 GeV would not have been discovered at the LHC, and this also holds for smaller s_α if additional decay channels are open. In this case, the limits become model dependent, and we leave this for future studies. As a first illustration of possible additional



$m_h = 125$ GeV, $m_H = 300$ GeV
(a)

$m_h = 75$ GeV, $m_H = 125$ GeV
(b)

Figure 3. The maximum $\mu_{\mathcal{H}\gamma\gamma}$ as described in the text, for (a) Case 1 and (b) Case 2, including experimental and theoretical constraints.

decay channels we calculate the branching ratios for H^0 for one point in parameter space, as shown in figure 2. It is clear that as soon as the $H^0 \to H^\pm W^\mp$ and/or $A^0 Z$ channels open, they will quickly dominate over the WW and ZZ channels, making H^0 more difficult to detect.

We are now in a position to consider the actually observed Higgs boson $\mathcal{H}$ in our model. Similar studies have been done of the Inert Doublet Model in refs. [29, 30].

The most significant channel observed is the $\gamma\gamma$ decay, where the ATLAS experiment has observed a slight excess in signal strength, $\mu = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst})$, where μ is the observed signal strength relative to the SM, at a mass of 126.8 GeV [3]. The overall best fit mass from all channels is 125.5 GeV. The CMS experiment, on the other hand, sees no excess, and has a combined best fit mass of 125.8 GeV [5].

The signal strength for $\mathcal{H} \to \gamma\gamma$ with $\mathcal{H} = h^0, H^0$, relative to the SM, is computed as

$$\mu_{\mathcal{H}\gamma\gamma} = \frac{\sum_i \sigma_i(pp \to \mathcal{H})\text{BR}(\mathcal{H} \to \gamma\gamma)}{\sum_i \sigma_i(pp \to H_{\text{SM}})\text{BR}(H_{\text{SM}} \to \gamma\gamma)} \tag{4.1}$$

where the sums run over all contributing production channels. The production cross sections for $gg \to \mathcal{H}$, vector-boson fusion, and associated production with a vector boson are all scaled in the same way compared to the SM: there is a suppression factor s_α^2 for h^0 and c_α^2 for H^0. The signal strength for $\mathcal{H} = h^0$ can then be written

$$\mu_{h^0\gamma\gamma} = s_\alpha^2 \frac{\text{BR}(h^0 \to \gamma\gamma)}{\text{BR}(H_{\text{SM}} \to \gamma\gamma)}, \tag{4.2}$$

and $\mu_{H^0\gamma\gamma}$ is obtained in the same way, but replacing $s_\alpha^2 \to c_\alpha^2$. Unlike the case for the tree-level decays of the H^0 discussed above, the branching ratios here are not equal in the SM and in our model, as there are charged scalars running in the loops. We have performed a scan over λ_3 and λ_7, with $-5 \leq \lambda_3 \leq 5$ and $-5 \leq \lambda_7 \leq \min\{5, \lambda_7^{\max}\}$, and in figure 3 plot the maximum obtained signal strength provided that the theoretical, LEP, Tevatron and 7 TeV LHC constraints are fulfilled. We plot this in the $(m_{H^\pm}, s_\alpha)$ plane for Cases 1 and 2 discussed above, fixing $m_H = 300$ GeV for Case 1 and $m_h = 75$ GeV for Case 2. The remaining parameter to be fixed is m_A. In order to fulfill the EWPT constraints discussed above, we take, for Case 1, $m_A = m_{H^\pm} + 50$ GeV if $m_{H^\pm}^2 < M^2$ or $m_A = m_{H^\pm}$ if $m_{H^\pm}^2 > M^2$, respectively (where M^2 was defined above), and for Case 2, we fix $m_A = m_{H^\pm}$. If m_h in Case 2 is increased, the sharp limit at $s_\alpha \sim 0.2$ is shifted upwards. We have not included off-shell decays $\mathcal{H} \to H^{+(*)}H^{-(*)}$ or $A^{0(*)}A^{0(*)}$ since the widths of the $H^\pm$ and A^0 are very small.

From figure 3 we see that in order to have a maximal signal strength of one or larger, in Case 1, we need $s_\alpha \gtrsim 0.8$, and in Case 2 we need $s_\alpha \lesssim 0.2$. The enhancements are driven by light $H^\pm$ in the loop, with couplings to the CP-even scalars $g_{hH^+H^-} = -\mathrm{i}v(-s_\alpha\lambda_3 + c_\alpha\lambda_7)$ and $g_{HH^+H^-} = -\mathrm{i}v(c_\alpha\lambda_3 + s_\alpha\lambda_7)$. If the charged scalar in Case 1 is very light ($\lesssim 80$ GeV), then it is possible to have almost any value for the mixing down to $s_\alpha \sim 0.2$ in order to obtain the observed $\gamma\gamma$ signal strength. However, as discussed above, the signal strengths for $\mathcal{H} \to VV, f\bar{f}$ are given by $\mu_{h^0VV} = \mu_{h^0f\bar{f}} = s_\alpha^2$ and $\mu_{H^0VV} = \mu_{H^0f\bar{f}} = c_\alpha^2$ if $m_{H^\pm} > m_{\mathcal{H}}/2$. Therefore, from the observations of $\mathcal{H} \to ZZ$ and $\mathcal{H} \to WW$ at LHC, the low s_α region in figure 3a is disfavored.

Let us now comment on the phenomenology of the charged scalar. LEP has set limits on the mass: the model-independent limit from the Z width is $m_{H^\pm} > 39.6$ GeV [31], and there is a limit of $m_{H^\pm} \gtrsim 80$ GeV [31–33] under the assumption that $\mathrm{BR}(H^+ \to \tau^+\nu)+\mathrm{BR}(H^+ \to c\bar{s}) = 1$. The charged scalar in our model has no tree-level fermion couplings, and does not primarily decay into $\tau\nu$ or tb as in the MSSM. The available tree-level couplings are to gauge bosons and scalars, but the decays $H^\pm \to W^\pm\gamma$ and $H^\pm \to W^\pm Z$ are not allowed at the tree-level due to gauge and isospin invariance, respectively. The only possible tree-level decays are therefore to final states including at least one other scalar, which can be possibly off-shell leading to many-body final states. The usual decay channels $\tau\nu$ and tb can indeed be generated at the one-loop level, but then we must also consider final states such as $W^\pm\gamma$ and $W^\pm Z$. In [10] we will perform a detailed study of these issues, but we note here that only the model independent LEP bound of 39.6 GeV applies, and that the $H^\pm \to W^\pm\gamma$ decay plays an important role, leading to a very interesting phenomenology.

5 Conclusions

In the Stealth Doublet Model presented in this paper, the A^0 and $H^\pm$ have no tree-level Yukawa couplings to fermions, so all such couplings are loop-suppressed. Flavor and LEP constraints therefore do not apply, and A^0 and $H^\pm$ can be lighter than in standard 2HDMs.

The CP-even scalars h^0 and H^0 on the other hand, have very similar couplings to standard 2HDMs. We find that either the h^0 or the H^0 can play the role of the Higgs boson that has been observed at the LHC, and refer to these cases as Case 1 for h^0 and Case 2 for H^0. In both cases there are large allowed regions of parameter space where the observed $\mathcal{H} \to \gamma\gamma$ signal strength is obtained.

The phenomenology of the model depends on the mixing of the CP-even scalars, given by the parameter s_α, which also controls the amount of soft breaking of the $\mathbb{Z}_2$ symmetry; if $s_\alpha \to 0$ or 1, we recover the Inert Doublet Model. In the two cases considered, when the observed $\mathcal{H} = h^0$, the data imply $s_\alpha \gtrsim 0.8$, and when $\mathcal{H} = H^0$, $s_\alpha \lesssim 0.2$ (valid for $m_h = 75$ GeV). The masses of the charged and CP-odd scalars are constrained from the oblique parameters ($m_{H^\pm} \approx m_A$ or $m_{H^\pm}^2 \approx m_h^2 c_\alpha^2 + m_H^2 s_\alpha^2$) and tree-level unitarity ($m_{H^\pm}, m_A \lesssim 700$ GeV). Moreover, $m_{H^\pm} \gtrsim m_{\mathcal{H}}/2$ is needed to obtain the observed $\gamma\gamma$ signal strength.

It is interesting to note that the parameter space that allows a signal strength for $\mathcal{H} \to \gamma\gamma$ of the same magnitude as the one observed at the LHC, is also the same parameter space ($s_\alpha \gtrsim 0.8$) where the H^0 of Case 1 is safe from having been excluded. If Case 1 of our model is realized in Nature, we can therefore expect a discovery of the H^0 boson in the $H^0 \to WW, ZZ$, $H^\pm W^\mp$ or $A^0 Z$ decay channels with more collected luminosity. If Case 2 is realized, we must instead look for a lighter h^0 boson. We will return to these issues and the study of the $H^\pm$ and A^0 in a forthcoming publication [10].

Acknowledgments

We thank A. Arhrib, T. Hahn, and R. Pasechnik for helpful discussions. RE and JR are supported by the Swedish Research Council under contracts 2007-4071 and 621-2011-5333.

References

[1] **ATLAS** Collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys.Lett.* **B716** (2012) 1–29, [arXiv:1207.7214].

[2] **CMS** Collaboration, S. Chatrchyan et al., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys.Lett.* **B716** (2012) 30–61, [arXiv:1207.7235].

[3] **ATLAS** Collaboration, *Measurements of the properties of the Higgs-like boson in the two photon decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data*, Tech. Rep. ATLAS-CONF-2013-012, CERN, Geneva, Mar, 2013.

[4] **ATLAS** Collaboration, *Measurements of the properties of the Higgs-like boson in the four lepton decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data*, Tech. Rep. ATLAS-CONF-2013-013, CERN, Geneva, Mar, 2013.

[5] **CMS** Collaboration, *Updated measurements of the Higgs boson at 125 GeV in the two photon decay channel*, Tech. Rep. CMS-PAS-HIG-13-001, CERN, Geneva, 2013.

[6] G. Branco et al., *Theory and phenomenology of two-Higgs-doublet models*, *Phys.Rept.* **516** (2012) 1–102, [arXiv:1106.0034].

[7] N. G. Deshpande and E. Ma, *Pattern of Symmetry Breaking with Two Higgs Doublets*, *Phys.Rev.* **D18** (1978) 2574.

[8] E. Ma, *Verifiable radiative seesaw mechanism of neutrino mass and dark matter*, *Phys.Rev.* **D73** (2006) 077301, [hep-ph/0601225].

[9] R. Barbieri, L. J. Hall, and V. S. Rychkov, *Improved naturalness with a heavy Higgs: An Alternative road to LHC physics*, *Phys.Rev.* **D74** (2006) 015007, [hep-ph/0603188].

[10] R. Enberg, J. Rathsman, and G. Wouda in preparation.

[11] G. Wouda, *Charged scalars in a lopsided doublet model*, *PoS* **CHARGED2010** (2010) 032.

[12] S. Davidson and H. E. Haber, *Basis-independent methods for the two-Higgs-doublet model*, *Phys. Rev.* **D72** (2005) 035004, [hep-ph/0504050]. *Erratum:* Phys. Rev. **D72** 099902 (2005).

[13] H. E. Haber and D. O'Neil, *Basis-independent methods for the two-Higgs-doublet model. II: The significance of tan(beta)*, *Phys. Rev.* **D74** (2006) 015018, [hep-ph/0602242]. *Erratum:* Phys. Rev. **D74** 059905(E) (2006).

[14] I. Ivanov, *Two-Higgs-doublet model from the group-theoretic perspective*, *Phys.Lett.* **B632** (2006) 360–365, [hep-ph/0507132].

[15] J. Bijnens, J. Lu, and J. Rathsman, *Constraining General Two Higgs Doublet Models by the Evolution of Yukawa Couplings*, *JHEP* **1205** (2012) 118, [arXiv:1111.5760].

[16] D. Eriksson, J. Rathsman, and O. Stål, *2HDMC: Two-Higgs-Doublet Model Calculator Physics and Manual*, *Comput.Phys.Commun.* **181** (2010) 189–205, [arXiv:0902.0851].

[17] D. Eriksson, J. Rathsman, and O. Stål, *2HDMC: Two-Higgs-doublet model calculator*, *Comput.Phys.Commun.* **181** (2010) 833–834.

[18] M. Sher, *Electroweak Higgs Potentials and Vacuum Stability*, *Phys. Rept.* **179** (1989) 273–418.

[19] H. Huffel and G. Pocsik, *Unitarity bounds on Higgs boson masses in the Weinberg- Salam model with two higgs doublets*, *Zeit. Phys.* **C8** (1981) 13.

[20] J. Maalampi, J. Sirkka, and I. Vilja, *Tree level unitarity and triviality bounds for two Higgs models*, *Phys. Lett.* **B265** (1991) 371–376.

[21] S. Kanemura, T. Kubota, and E. Takasugi, *Lee-Quigg-Thacker bounds for Higgs boson masses in a two doublet model*, *Phys. Lett.* **B313** (1993) 155–160, [hep-ph/9303263].

[22] A. G. Akeroyd, A. Arhrib, and E.-M. Naimi, *Note on tree-level unitarity in the general two Higgs doublet model*, *Phys. Lett.* **B490** (2000) 119–124, [hep-ph/0006035].

[23] **Particle Data Group** Collaboration, J. Beringer et al., *Review of Particle Physics (RPP)*, *Phys.Rev.* **D86** (2012) 010001.

[24] M. E. Peskin and T. Takeuchi, *Estimation of oblique electroweak corrections*, *Phys. Rev.* **D46** (1992) 381–409.

[25] P. Bechtle et al., *HiggsBounds: Confronting Arbitrary Higgs Sectors with Exclusion Bounds from LEP and the Tevatron*, *Comput. Phys. Commun.* **181** (2010) 138–167, [arXiv:0811.4169].

[26] P. Bechtle et al., *HiggsBounds 2.0.0: Confronting Neutral and Charged Higgs Sector Predictions with Exclusion Bounds from LEP and the Tevatron*, *Comput. Phys. Commun.* **182** (2011) 2605–2631, [arXiv:1102.1898].

[27] P. Bechtle et al., *Recent Developments in HiggsBounds and a Preview of HiggsSignals*, *PoS* **CHARGED2012** (2013) 024, [arXiv:1301.2345].

[28] F. Mahmoudi and O. Stål, *Flavor constraints on the two-Higgs-doublet model with general Yukawa couplings*, arXiv:0907.1791.

[29] B. Swiezewska and M. Krawczyk, *Diphoton rate in the Inert Doublet Model with a 125 GeV Higgs boson*, arXiv:1212.4100.

[30] A. Goudelis, B. Herrmann, and O. Stål, *Dark matter in the Inert Doublet Model after the discovery of a Higgs-like boson at the LHC*, arXiv:1303.3010.

[31] **DELPHI Collaboration** Collaboration, J. Abdallah et al., *Search for charged Higgs bosons at LEP in general two Higgs doublet models*, *Eur.Phys.J.* **C34** (2004) 399–418, [hep-ex/0404012].

[32] **ALEPH Collaboration** Collaboration, A. Heister et al., *Search for charged Higgs bosons in e^+e^- collisions at energies up to $\sqrt{s}$ = 209-GeV*, *Phys.Lett.* **B543** (2002) 1–13, [hep-ex/0207054].

[33] **ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, The LEP working group for Higgs boson searches** Collaboration, G. Abbiendi et al., *Search for Charged Higgs bosons: Combined Results Using LEP Data*, *Eur.Phys.J.C* (2013) [arXiv:1301.6065].