Proposal for singlet benchmark scenarios in the RxSM and CxSM

Raul Costa[1 *], **Margarete Mühlleitner**[2 †], **Marco O.P. Sampaio**[3 ‡] and **Rui Santos**[1, 4 §]

[1] *Centro de Física Teórica e Computacional, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, Edifício C8 1749-016 Lisboa, Portugal*
[2] *Institute for Theoretical Physics, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany*
[3] *Departamento de Física da Universidade de Aveiro and CIDMA, Campus de Santiago, 3810-183 Aveiro, Portugal*
[4] *ISEL - Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa 1959-007 Lisboa, Portugal*

We propose benchmark scenarios for the real (RxSM) and complex singlet (CxSM) models with and without dark matter, for the LHC run 2. Points which are visible at the 13 TeV run are chosen such that scalar to scalar decays are maximised allowing for the new states to be detected directly or in their chain decays to the 125 GeV boson. All scenarios where the latter is the lightest, the next to lightest or heaviest of the scalars are covered. When dark matter is present it is chosen as to reproduce the Planck measurement of the relic density.

[*] E-mail: `rauljcosta@ua.pt`
[†] E-mail: `margarete.muehlleitner@kit.edu`
[‡] E-mail: `msampaio@ua.pt`
[§] E-mail: `rasantos@fc.ul.pt`

1 Introduction

The complex singlet extension of the Standard Model, CxSM, is the simplest extension which provides a scenario of Higgs pair production with different masses. The CxSM has two interesting phases: the dark matter phase, and the broken phase where all neutral scalars mix. In the dark matter phase, besides the Standard Model like (SM-like) Higgs there is a dark matter candidate plus an extra scalar. However, it is in the broken phase, with one Higgs boson plus two other massive non-dark scalars that such a scenario occurs.

In the SM, the double Higgs production cross section is very small and even at the high luminosity stage of the LHC it will be extremely hard to measure the triple Higgs coupling [1]. However, in many beyond the SM (BSM) scenarios, resonant decays are possible due to the existence of other scalar particles in the theory. In such cases, the chances of observing a final state with two scalars increase considerably. The simplest extension of the SM where a double Higgs final state would be detectable at the LHC is the singlet extension of the SM, where a hypercharge zero singlet is added to the scalar model field content. When the singlet is real, one either obtains a new scalar mixing with the Higgs boson, or the minimal model for dark matter. Furthermore, the model can also accommodate electroweak baryogenesis by allowing a strong first-order phase transition during the era of electroweak symmetry breaking, if the singlet is complex.

In defining the benchmarks we are guided by two goals. The first is to maximize at least one of the scalar to two scalars decays. The second is related to stability of the theory at higher orders. As discussed in [2], the radiative stability of the model, at two-loops, up to a high energy scale, combined with the constraint that the 125 GeV Higgs boson found at the LHC is in the spectrum, forces the new scalar to be heavy. When we include all experimental and observational constraints/measurements from collider data, dark matter direct detection experiments and from the Planck satellite and in addition force stability at least up to the GUT scale, we find that the lower bound on the new scalar is about 170 GeV.

2 The models

In this section we define the reference complex (CxSM) and real (RxSM) singlet models that we will analyse to define benchmarks.

2.1 The CxSM

We start with a discussion of the a complex singlet model because the real singlet model is similar (except for the invisible decays) to the visible sector of the dark matter phase of this model. The complex singlet model we consider [2–15] is a simple extension of the SM where a complex singlet field $\mathbb{S} = S + iA$ with hypercharge zero, is added to the SM field content. All new interactions are determined by the scalar potential, which can be seen as a model with a $U(1)$ global symmetry which is broken softly. The scalar potential is

$$V_{\rm CxSM} = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2}H^\dagger H|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1\mathbb{S} + c.c.\right) , \quad (1)$$

where the soft breaking terms are shown in parenthesis and the doublet and complex singlet are

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} \quad , \quad \mathbb{S} = \frac{1}{\sqrt{2}} \left[v_S + s + i(v_A + a) \right] \ . \tag{2}$$

Here $v \simeq 246$ GeV is the SM Higgs vacuum expectation value (VEV), and v_S, v_A are, respectively, the real and imaginary parts of the complex singlet field VEV.

In [3], the various phases of the model were discussed. In order to classify them it is convenient to treat the real and complex components of the complex singlet as independent, which is equivalent to building a model with two real singlet fields. We focus on a version of the model which is obtained by requiring a $\mathbb{Z}_2$ symmetry for the imaginary component A. This is equivalent to imposing a symmetry under $\mathbb{S} \to \mathbb{S}^*$. As a consequence of this symmetry, the soft breaking couplings must be both real, i.e. $a_1 \in \mathbb{R}$ and $b_1 \in \mathbb{R}$. By analysing the minimum conditions one finds two possible phases which are consistent with an electroweak symmetry breaking to trigger the Higgs mechanism. They are:

- $v_A = 0$ and $v_S \neq 0$, in which case mixing between the doublet field h and the real component s of the singlet field occurs, while the imaginary component $A = a$ becomes a dark matter candidate. We call this the symmetric or *dark matter phase*.
- $\langle \mathbb{S} \rangle \neq 0$ ($v_S \neq 0$ and $v_A \neq 0$), which we call the *broken phase*, with no dark matter candidate and mixing among all scalars.

From the phenomenological point of view, the model presented here covers all possible scenarios in terms of the accessible physical processes to be probed at the LHC in a model with three scalars.

Physical states and couplings

To obtain the couplings of the theory to the SM particles, we define the mass eigenstates as h_i ($i = 1, 2, 3$), which are obtained from the gauge eigenstates h, s and a through the mixing matrix R

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} h \\ s \\ a \end{pmatrix} , \tag{3}$$

with

$$R \, \mathcal{M}^2 \, R^T = \mathrm{diag} \left(m_1^2, m_2^2, m_3^2 \right) , \tag{4}$$

and where $m_1 \leq m_2 \leq m_3$ are the masses of the neutral Higgs particles. The mixing matrix R is parametrized as

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} \tag{5}$$

with $s_i = \sin \alpha_i$ and $c_i = \cos \alpha_i$ ($i = 1, 2, 3$) and

$$-\pi/2 < \alpha_1 \leq \pi/2, \qquad -\pi/2 < \alpha_2 \leq \pi/2, \qquad -\pi/2 \leq \alpha_3 \leq \pi/2. \tag{6}$$

The couplings of h_i to the SM particles are all modified by the same matrix element R_{i1}, that is, for any SM coupling $\lambda^{(p)}_{h_{SM}}$, where p runs over all SM fermions and gauge bosons, the corresponding coupling in the singlet model for the scalar h_i is given by

$$\lambda_i^{(p)} = R_{i1} \lambda^{(p)}_{h_{SM}} \,, \tag{7}$$

so it is independent of the specific SM particle to which the coupling corresponds.

In the dark matter phase, $\alpha_2 = \alpha_3 = 0$ and $h_3 = A = a$ is the dark matter candidate which does not mix with h nor with s. Regarding the couplings to SM particles the same arguments apply with $R_{i1} = (R_{11}, R_{21}, 0)$. The dark matter candidate does not couple to the SM fermions and gauge bosons since $R_{31} = 0$. The couplings that remain to define are the scalar sector ones, which are read directly from the scalar potential, Eq. (1), after replacing the choice of vacua, Eq. (2).

Which parameters one uses as independent is to some extent a matter of convenience. In the implementation of the decays in sHDECAY [16] we have opted to choose as many observable parameters as possible as input values (masses and mixing angles). For the broken phase we choose the set $\{\alpha_1, \alpha_2, \alpha_3, m_1, m_3, v, v_S\}$ and for the dark phase the set $\{\alpha, m_1, m_2, m_3 \equiv m_A, v, v_S, a_1\}$.

2.2 The RxSM

We consider the real singlet model [17–31]. This model is obtained by adding a real singlet S with a $\mathbb{Z}_2$ symmetry ($S \to -S$) to the SM. Then the most general renormalisable potential is

$$V_{\rm RxSM} = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4} (H^\dagger H)^2 + \frac{\lambda_{HS}}{2} H^\dagger H S^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4 \,. \tag{8}$$

Electroweak symmetry breaking (with a vacuum consistent with the Higgs mechanism) occurs via the following choices

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} \quad , \quad S = v_S + s \,, \tag{9}$$

where $v \simeq 246$ GeV is the SM Higgs VEV, and v_S is the singlet VEV. In this model, we are primarily interested in the broken phase, $v_S \neq 0$, where we use a notation $\{m_1, m_2\}$ for the scalar states (ordered in mass) that mix h with s. The two-by-two mixing matrix can be parametrised in the same way as the sub-block obtained in the dark phase of the complex singlet, i.e. when $\alpha_1 \equiv \alpha$ and $\alpha_2 = \alpha_3 = 0$.

In the symmetric phase, $m_1 \equiv m_h$ (the observed Higgs boson) and $m_2 \equiv m_A$ (the dark matter candidate). We will, however, not focus on this phase since it does not contain any new visible scalar decays.

Regarding couplings, everything is similar to the CxSM, i.e. the couplings of the various scalars are controlled by the same rule, Eq. (7), with R_{i1} being the corresponding elements of the reduced two-by-two mixing matrix. The couplings among scalars are again read directly from the potential of the model, Eq. (8), after replacing the choice of vacua, Eq. (9). For the parameter space scans of this model we note that the model has five independent parameters. In the implementation of the decays for the broken phase of the RxSM in sHDECAY [16] we choose the set $\{\alpha_1 \equiv \alpha, m_1, m_2, v, v_S\}$.

3 Constraints

The constraints we apply to the models under study are of three types: i) Theoretical constraints, which are necessary for the consistency of the model, ii) exclusion bounds, which set limits on model parameters from negative searches and iii) consistency with signal measurements. In certain situations, the latter can also be interpreted as a source of bounds on new Physics contributions. All these constraints were discussed in detail in [3] and recently updated in [2]. One important comment is that we have turned off consistently the higher order electroweak corrections both in the gluon fusion cross-section and in the scalar decays.

4 Benchmarks

In this section we provide a set of benchmark points. We start with the RxSM because it is simpler in terms of scalar to scalars decay possibilities and then present the CxSM.

In such singlet models, at leading order in the electroweak corrections, the production cross-sections and decays to SM particles follow a simple rule: they are given by multiplying the SM result by the squared mixing matrix element R_{i1}^2, cf. Eq. (7). Thus, within this approximation, there is only one common signal strength factor regardless of the decay channel to SM particles (i.e. direct decays). Such signal strength provides a useful measure for the deviation of the model point from the SM. One can show that it is given by

$$\mu_i = R_{ih}^2 \sum_{X_{\rm SM}} {\rm BR}(h_i \to X_{\rm SM}) \,, \tag{10}$$

in other words it is the squared overlap of the scalar state with the SM Higgs fluctuation (i.e. the mixing matrix element) multiplied by the branching ratio for the decay to any SM particle. If there are no scalar to scalars decays the latter factor is one.

4.1 RxSM

We show for this model all possible kinematically different situations in table 1. The two points to the left correspond to the case where the SM-like Higgs is the lightest of the two mixing scalar states. Benchmark RxSM.B1 allows for the decay $h_2 \to h_1 h_1$ and we have chosen a point with a relatively large cross-section for such chain decay which is comparable to the direct decays. Thus the h_2 scalar could in principle be found directly or in its chain decays. For completeness, we also display in RxSM.B2 a point where the channel is closed, but instead various direct decay channels of the h_2 are enhanced.

In the two rightmost benchmarks (RxSM.B3 and RxSM.B4), we also show the two possible cases when the observed Higgs is the heaviest of the two scalars. RxSM.B3 was again chosen such that the new h_1 can be found both directly or in the decay $h_2 \to h_1 h_1$. The point RxSM.B4 is the same scenario but with the chain decay channel closed.

	RxSM.B1	RxSM.B2	RxSM.B3	RxSM.B4
$\star\ m_1$ (GeV)	125.4	125.4	36.283	117.19
$\star\ m_2$ (GeV)	279.65	176.3	125.4	125.4
$\star\ \alpha$	-0.54065	-0.46964	1.4272	-0.97629
$\star\ v_S$ (GeV)	209.97	995.11	357.45	84.837
λ	1.0648	0.62253	0.50904	0.49815
λ_{HS}	0.53333	0.025292	-0.023182	0.044269
λ_S	4.1955	0.084633	0.037835	5.9845
m^2 (GeV^2)	-55789	-43916	-12468	-15419
m_S^2 (GeV^2)	-46994	-14735	-103	-8520.6
μ_{h_1}	0.735	0.795	0.0205	0.314
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	23.2 [pb]	25.1 [pb]	7.26 [pb]	11.2 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.62 [pb]	5 [pb]	0.0162 [fb]	1.07 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	581 [fb]	629 [fb]	< 0.01 [fb]	115 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	14.2 [pb]	15.3 [pb]	6.38 [pb]	8 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.36 [pb]	1.47 [pb]	475 [fb]	758 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	50.1 [fb]	54.2 [fb]	1.08 [fb]	22.7 [fb]
μ_{h_2}	0.148	0.205	0.66	0.686
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	2.09 [pb]	3.48 [pb]	30.9 [pb]	21.6 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	810 [fb]	3.31 [pb]	4.15 [pb]	4.32 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	354 [fb]	130 [fb]	522 [fb]	543 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.972 [fb]	24.6 [fb]	12.7 [pb]	13.2 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.109 [fb]	2.52 [fb]	1.22 [pb]	1.27 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0196 [fb]	0.429 [fb]	45 [fb]	46.8 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	920 [fb]	0	10.1 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	344 [fb]	0	7.79 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	66.1 [fb]	0	1.16 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	225 [fb]	0	0.0395 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	2.43 [fb]	0	2.63 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	3.17 [fb]	0	43.2 [fb]	0

Table 1: *Benchmark points for the RxSM (broken phase):* The parameters of the theory that we take as input values are denoted with a star ($\star$). The cross-sections are for $\sqrt{s} \equiv 13$ TeV.

4.2 CxSM

4.2.1 Dark matter phase

In table 2 we have selected three points with the relic density such that it agrees with the Planck measurement (this was computed with MICROMEGAs [32, 33]). The first two points have the SM-like Higgs as the lightest of the two visible scalars. In point CxSM.D1, both visible scalars can decay invisibly whereas for point CxSM.D2 h_1 cannot. We chose large invisible decay cross-sections but also a large chain decay $h_2 \to h_1 h_1$. Point CxSM.D1 has the largest invisible decay for h_1 and we have also chosen a large invisible decay for h_2 in CxSM.D2. Furthermore, both have large cross sections for direct production of h_2 and so the chain decays would be complementary to the direct discovery. It is interesting to note that the two heavy scalars stabilise the theory up to a high scale, respectively 10^{12} and 10^{14} GeV.

	CxSM.D1	CxSM.D2	CxSM.D3
$\star\ m_1$ (GeV)	125.4	125.4	49.116
$\star\ m_2$ (GeV)	456.57	339.77	125.4
$\star\ m_A$ (GeV)	52.98	77.022	65.054
$\star\ \alpha$	-0.39506	-0.50029	1.4617
$\star\ v_S$ (GeV)	766.84	553.5	341.32
λ	1.4606	1.2757	0.51357
δ_2	0.7252	0.61592	-0.034278
d_2	0.58451	0.55	0.042823
m^2 (GeV^2)	-2.575×10^5	-1.3302×10^5	-13571
b_2 (GeV^2)	-1.8298×10^5	-88740	2852.4
b_1 (GeV^2)	5245.8	2315.6	-4156.4
$\star\ a_1$ (GeV^3)	-4.3665×10^6	-3.2282×10^6	-18263
$\Omega_A h^2$	0.115	0.116	0.115
μ_{h_1}	0.852	0.77	0.0118
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	26.9 [pb]	24.3 [pb]	2.14 [pb]
$\sigma_1 \times \text{BR}(h_1 \to WW)$	4.59 [pb]	4.84 [pb]	0.0346 [fb]
$\sigma_1 \times \text{BR}(h_1 \to ZZ)$	577 [fb]	609 [fb]	0.011 [fb]
$\sigma_1 \times \text{BR}(h_1 \to bb)$	14.1 [pb]	14.9 [pb]	1.87 [pb]
$\sigma_1 \times \text{BR}(h_1 \to \tau\tau)$	1.35 [pb]	1.43 [pb]	148 [fb]
$\sigma_1 \times \text{BR}(h_1 \to \gamma\gamma)$	49.7 [fb]	52.5 [fb]	0.608 [fb]
$\sigma_1 \times \text{BR}(h_1 \to AA)$	3.84 [pb]	0	0
μ_{h_2}	0.0977	0.135	0.743
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	698 [fb]	1.6 [pb]	31.2 [pb]
$\sigma_2 \times \text{BR}(h_2 \to WW)$	251 [fb]	642 [fb]	4.67 [pb]
$\sigma_2 \times \text{BR}(h_2 \to ZZ)$	119 [fb]	292 [fb]	587 [fb]
$\sigma_2 \times \text{BR}(h_2 \to bb)$	0.0764 [fb]	0.432 [fb]	14.3 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \tau\tau)$	< 0.01 [fb]	0.0501 [fb]	1.38 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \gamma\gamma)$	< 0.01 [fb]	< 0.01 [fb]	50.6 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1)$	155 [fb]	429 [fb]	7.74 [pb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bbbb)$	42.7 [fb]	160 [fb]	5.89 [pb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	8.19 [fb]	30.8 [fb]	932 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bbWW)$	27.8 [fb]	105 [fb]	0.218 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	0.302 [fb]	1.13 [fb]	3.83 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.393 [fb]	1.48 [fb]	36.9 [fb]
$\sigma_2 \times \text{BR}(h_2 \to AA)$	0.0822 [pb]	0.233 [pb]	0

Table 2: *Benchmark points for the CxSM (dark phase):* The parameters of the theory that we take as input values are denoted with a star ($\star$). The cross-sections are for $\sqrt{s} \equiv 13$ TeV.

Point CxSM.D3 does not contain invisible decays, and the SM-like Higgs is the heaviest visible scalar. This is also a case where the indirect discovery of h_1 through the Higgs decay $h_2 \to h_1 h_1$ is possible given the large cross sections for chain decays with $bbbb$ and $bb\tau\tau$ final states. Though the point cannot be stable up to the GUT scale, a UV completion only has to be provided at 10^8 GeV, for this particular point.

4.2.2 Broken phase

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
$\star$ m_1 (GeV)	125.4	125.4	57.34	98.12	41.61
m_2 (GeV)	258.9	230.8	125.4	125.4	69.51
$\star$ m_3 (GeV)	462.4	271.3	345.5	255.2	125.4
$\star$ α_1	-0.04867	0.03148	-1.071	-0.7888	-1.169
$\star$ α_2	0.4739	-0.5707	1.126	0.7717	1.24
$\star$ α_3	-0.4763	-0.3888	-0.005447	-0.1945	1.044
$\star$ v_S (GeV)	42.03	11.53	412.6	107.9	250.9
v_A (GeV)	110.3	92.86	257.8	168.9	559.3
λ	1.584	1.041	1.127	0.6614	0.504
δ_2	-4.807	2.167	-0.6748	-0.6795	-0.03074
d_2	24.37	12.67	0.7469	2.606	0.01501
m^2 (GeV^2)	-1.455×10^4	-4.103×10^4	4.569×10^4	-6395	-9502
b_2 (GeV^2)	5.491×10^4	-6.562×10^4	-5.208×10^4	-1.371×10^4	2302
b_1 (GeV^2)	7.89×10^4	5.556×10^4	1.585×10^4	1.806×10^4	4191
a_1 (GeV^3)	-2.345×10^6	-4.531×10^5	-4.624×10^6	-1.378×10^6	-7.434×10^5

Table 3: *Benchmark points for the CxSM (broken phase):* The parameters of the theory that we take as input values are denoted with a star ($\star$). The cross-sections are for $\sqrt{s} \equiv 13$ TeV.

In tables 3 and 4 we show a sample of various kinematically allowed situations for the three mixing scalars of the broken phase of the CxSM. We have chosen: two points where the SM-like Higgs is the lightest (CxSM.B1 and CxSM.B2); two points where it is the next to lightest (CxSM.B3 and CxSM.B4); and one point where it is the heaviest (CxSM.B5). An interesting feature is that there are points for which the model remains stable up to a large scale. The numbers are, respectively for each point, 10^4 GeV, 10^5 GeV, 10^{16} GeV, 10^9 GeV and 10^7 GeV. The most interesting one is CxSM.B3, since the new heavy scalar stabilises the theory up to the GUT scale (10^{16} GeV).

Most points were chosen such that the cross-section for the channel $h_3 \to h_2 h_1$ is relatively large (most notably CxSM.B1, CxSM.B4 and CxSM.B5), so that discovery of h_3 through decays proceeding through this channel can compete with the direct decay of h_3 (see CxSM.B1 and CxSM.B4 in tables 3 and 4). For the points where new scalars lighter than the SM-like Higgs are present (CxSM.B4 and CxSM.B5) we have chosen points with large cross-sections for the new light scalars, so that they can also be detected directly.

References

[1] A. Djouadi, W. Kilian, M. Muhlleitner, and P. M. Zerwas. Production of neutral Higgs boson pairs at LHC. *Eur. Phys. J.*, C10:45–49, 1999.

[2] Raul Costa, Antnio P. Morais, Marco O. P. Sampaio, and Rui Santos. Two-loop stability of a complex singlet extended Standard Model. *Phys. Rev.*, D92(2):025024, 2015.

[3] Rita Coimbra, Marco O.P. Sampaio, and Rui Santos. ScannerS: Constraining the phase diagram of a complex scalar singlet at the LHC. *Eur.Phys.J.*, C73:2428, 2013.

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
μ_{h_1}	0.79	0.707	0.0426	0.255	0.0161
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	24.9 [pb]	22.3 [pb]	5.67 [pb]	12.5 [pb]	4.19 [pb]
$\sigma_1 \times \text{BR}(h_1 \to WW)$	4.97 [pb]	4.45 [pb]	0.262 [fb]	87.4 [fb]	0.0226 [fb]
$\sigma_1 \times \text{BR}(h_1 \to ZZ)$	625 [fb]	560 [fb]	0.0807 [fb]	10 [fb]	$<$ 0.01 [fb]
$\sigma_1 \times \text{BR}(h_1 \to bb)$	15.2 [pb]	13.6 [pb]	4.91 [pb]	10.2 [pb]	3.67 [pb]
$\sigma_1 \times \text{BR}(h_1 \to \tau\tau)$	1.46 [pb]	1.31 [pb]	401 [fb]	936 [fb]	281 [fb]
$\sigma_1 \times \text{BR}(h_1 \to \gamma\gamma)$	53.8 [fb]	48.2 [fb]	2.26 [fb]	17.4 [fb]	0.831 [fb]
μ_{h_2}	0.0636	0.0547	0.768	0.626	0.0205
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	559 [fb]	577 [fb]	24.4 [pb]	19.7 [pb]	1.88 [pb]
$\sigma_2 \times \text{BR}(h_2 \to WW)$	390 [fb]	408 [fb]	4.87 [pb]	3.95 [pb]	0.342 [fb]
$\sigma_2 \times \text{BR}(h_2 \to ZZ)$	167 [fb]	167 [fb]	613 [fb]	497 [fb]	0.0998 [fb]
$\sigma_2 \times \text{BR}(h_2 \to bb)$	0.601 [fb]	0.928 [fb]	14.8 [pb]	12.1 [pb]	1.61 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \tau\tau)$	0.0663 [fb]	0.1 [fb]	1.42 [pb]	1.16 [pb]	137 [fb]
$\sigma_2 \times \text{BR}(h_2 \to \gamma\gamma)$	0.0122 [fb]	0.0186 [fb]	52.4 [fb]	42.7 [fb]	1.15 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1)$	0.0467 [fb]	0	195 [fb]	0	0
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.0175 [fb]	0	146 [fb]	0	0
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	$<$ 0.01 [fb]	0	23.9 [fb]	0	0
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bbWW)$	0.0114 [fb]	0	0.0156 [fb]	0	0
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	0	0.134 [fb]	0	0
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	$<$ 0.01 [fb]	0	0.976 [fb]	0	0
μ_{h_3}	0.0774	0.0868	0.111	0.0273	0.777
$\sigma_3 \equiv \sigma(gg \to h_3)$ 13 TeV	659 [fb]	1.95 [pb]	1.31 [pb]	1.07 [pb]	30.4 [pb]
$\sigma_3 \times \text{BR}(h_3 \to WW)$	189 [fb]	496 [fb]	537 [fb]	172 [fb]	4.89 [pb]
$\sigma_3 \times \text{BR}(h_3 \to ZZ)$	89.7 [fb]	215 [fb]	245 [fb]	73.2 [fb]	615 [fb]
$\sigma_3 \times \text{BR}(h_3 \to bb)$	0.0558 [fb]	0.656 [fb]	0.345 [fb]	0.277 [fb]	15 [pb]
$\sigma_3 \times \text{BR}(h_3 \to \tau\tau)$	$<$ 0.01 [fb]	0.073 [fb]	0.0401 [fb]	0.0305 [fb]	1.44 [pb]
$\sigma_3 \times \text{BR}(h_3 \to \gamma\gamma)$	$<$ 0.01 [fb]	0.0133 [fb]	$<$ 0.01 [fb]	$<$ 0.01 [fb]	53 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1)$	3.75 [fb]	1.24 [pb]	280 [fb]	415 [fb]	5.47 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bbbb)$	1.4 [fb]	464 [fb]	210 [fb]	279 [fb]	4.2 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	0.269 [fb]	89 [fb]	34.4 [fb]	51 [fb]	643 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bbWW)$	0.915 [fb]	302 [fb]	0.0224 [fb]	4.76 [fb]	0.0518 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	3.28 [fb]	0.193 [fb]	0.948 [fb]	1.9 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.0129 [fb]	4.27 [fb]	1.41 [fb]	2.33 [fb]	24.6 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_2)$	307 [fb]	0	83.5 [fb]	408 [fb]	401 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_2 \to bbbb)$	0.202 [fb]	0	43.8 [fb]	204 [fb]	301 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_2 \to bb\tau\tau)$	0.0417 [fb]	0	7.78 [fb]	38.3 [fb]	48.7 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_2 \to bbWW)$	131 [fb]	0	14.4 [fb]	68.7 [fb]	0.0657 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_2 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	0	0.175 [fb]	1.07 [fb]	0.284 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_2 \to \tau\tau\tau\tau)$	$<$ 0.01 [fb]	0	0.344 [fb]	1.79 [fb]	1.96 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_2)$	0	0	151 [fb]	0.318 [fb]	0
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_2 \to bbbb)$	0	0	55.5 [fb]	0.119 [fb]	0
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_2 \to bb\tau\tau)$	0	0	10.6 [fb]	0.0228 [fb]	0
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_2 \to bbWW)$	0	0	36.6 [fb]	0.0776 [fb]	0
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_2 \to bb\gamma\gamma)$	0	0	0.393 [fb]	$<$ 0.01 [fb]	0
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_2 \to \tau\tau\tau\tau)$	0	0	0.511 [fb]	$<$ 0.01 [fb]	0

Table 4: *Benchmark points for the CxSM (broken phase):* Continuation of table 3.

[4] Anindya Datta and Amitava Raychaudhuri. Next-to-minimal Higgs: Mass bounds and search prospects. *Phys.Rev.*, D57:2940–2948, 1998.

[5] Robert Schabinger and James D. Wells. A Minimal spontaneously broken hidden sector and its impact on Higgs boson physics at the large hadron collider. *Phys.Rev.*, D72:093007, 2005.

[6] Omri Bahat-Treidel, Yuval Grossman, and Yoram Rozen. Hiding the Higgs at the LHC. *JHEP*, 0705:022, 2007.

[7] Vernon Barger, Paul Langacker, and Gabe Shaughnessy. Collider Signatures of Singlet Extended Higgs Sectors. *Phys.Rev.*, D75:055013, 2007.

[8] Vernon Barger, Paul Langacker, Mathew McCaskey, Michael J. Ramsey-Musolf, and Gabe Shaughnessy. LHC Phenomenology of an Extended Standard Model with a Real Scalar Singlet. *Phys.Rev.*, D77:035005, 2008.

[9] Vernon Barger, Paul Langacker, Mathew McCaskey, Michael Ramsey-Musolf, and Gabe Shaughnessy. Complex Singlet Extension of the Standard Model. *Phys.Rev.*, D79:015018, 2009.

[10] Donal O'Connell, Michael J. Ramsey-Musolf, and Mark B. Wise. Minimal Extension of the Standard Model Scalar Sector. *Phys.Rev.*, D75:037701, 2007.

[11] Rick S. Gupta and James D. Wells. Higgs boson search significance deformations due to mixed-in scalars. *Phys.Lett.*, B710:154–158, 2012.

[12] A. Drozd, B. Grzadkowski, and Jose Wudka. Multi-Scalar-Singlet Extension of the Standard Model - the Case for Dark Matter and an Invisible Higgs Boson. *JHEP*, 1204:006, 2012.

[13] Giovanni Marco Pruna and Tania Robens. The Higgs Singlet extension parameter space in the light of the LHC discovery. *Phys.Rev.*, D88:115012, 2013.

[14] Amine Ahriche, Abdesslam Arhrib, and Salah Nasri. Higgs Phenomenology in the Two-Singlet Model. *JHEP*, 1402:042, 2014.

[15] Chien-Yi Chen, S. Dawson, and I. M. Lewis. Exploring resonant di-Higgs boson production in the Higgs singlet model. *Phys. Rev.*, D91(3):035015, 2015.

[16] Raul Costa, Marco O. P. Guedes, Margarete Mhlleitner, and Rui Santos. sHDECAY, September 2015. `http://www.itp.kit.edu/~maggie/sHDECAY/`.

[17] Vanda Silveira and A. Zee. Scalar phantoms. *Phys.Lett.*, B161:136, 1985.

[18] John McDonald. Gauge singlet scalars as cold dark matter. *Phys.Rev.*, D50:3637–3649, 1994.

[19] C.P. Burgess, Maxim Pospelov, and Tonnis ter Veldhuis. The Minimal model of nonbaryonic dark matter: A Singlet scalar. *Nucl.Phys.*, B619:709–728, 2001.

[20] M.C. Bento, O. Bertolami, R. Rosenfeld, and L. Teodoro. Selfinteracting dark matter and invisibly decaying Higgs. *Phys.Rev.*, D62:041302, 2000.

[21] Hooman Davoudiasl, Ryuichiro Kitano, Tianjun Li, and Hitoshi Murayama. The New minimal standard model. *Phys.Lett.*, B609:117–123, 2005.

[22] Alexander Kusenko. Sterile neutrinos, dark matter, and the pulsar velocities in models with a Higgs singlet. *Phys.Rev.Lett.*, 97:241301, 2006.

[23] J.J. van der Bij. The Minimal non-minimal standard model. *Phys.Lett.*, B636:56–59, 2006.

[24] Xiao-Gang He, Tong Li, Xue-Qian Li, Jusak Tandean, and Ho-Chin Tsai. Constraints on Scalar Dark Matter from Direct Experimental Searches. *Phys.Rev.*, D79:023521, 2009.

[25] Matthew Gonderinger, Yingchuan Li, Hiren Patel, and Michael J. Ramsey-Musolf. Vacuum Stability, Perturbativity, and Scalar Singlet Dark Matter. *JHEP*, 1001:053, 2010.

[26] Y. Mambrini. Higgs searches and singlet scalar dark matter: Combined constraints from XENON 100 and the LHC. *Phys.Rev.*, D84:115017, 2011.

[27] Xiao-Gang He, Bo Ren, and Jusak Tandean. Hints of Standard Model Higgs Boson at the LHC and Light Dark Matter Searches. *Phys.Rev.*, D85:093019, 2012.

[28] Matthew Gonderinger, Hyungjun Lim, and Michael J. Ramsey-Musolf. Complex Scalar Singlet Dark Matter: Vacuum Stability and Phenomenology. *Phys.Rev.*, D86:043511, 2012.

[29] James M. Cline, Kimmo Kainulainen, Pat Scott, and Christoph Weniger. Update on scalar singlet dark matter. *Phys.Rev.*, D88:055025, 2013.

[30] Emidio Gabrielli, Matti Heikinheimo, Kristjan Kannike, Antonio Racioppi, Martti Raidal, et al. Towards Completing the Standard Model: Vacuum Stability, EWSB and Dark Matter. *Phys.Rev.*, D89:015017, 2014.

[31] Stefano Profumo, Michael J. Ramsey-Musolf, Carroll L. Wainwright, and Peter Winslow. Singlet-catalyzed electroweak phase transitions and precision Higgs boson studies. *Phys. Rev.*, D91(3):035018, 2015.

[32] G. Belanger, F. Boudjema, and A. Pukhov. micrOMEGAs : a code for the calculation of Dark Matter properties in generic models of particle interaction. 2014. https://lapth.cnrs.fr/micromegas/.

[33] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov. MicrOMEGAs 2.0: A Program to calculate the relic density of dark matter in a generic model. *Comput.Phys.Commun.*, 176:367–382, 2007.