Proposal for CP-violating benchmarks in the C2HDM

Duarte Fontes [1] *, **Jorge C. Romão** [1] †, **Rui Santos** [2,3] ‡ and **João P. Silva** [1] §

[1] *Departamento de Física and CFTP, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal*

[2] *Centro de Física Teórica e Computacional, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, Edifício C8 1749-016 Lisboa, Portugal*

[3] *ISEL - Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa 1959-007 Lisboa, Portugal*

Abstract

In this note we propose benchmark scenarios where using a combination of three decays, involving the 125 GeV Higgs boson, the Z boson and at least one more scalar, an indisputable signal of CP-violation arises in the framework of the complex two-Higgs doublet model. The note is based on [1] where a more detailed description of the model and benchmarks can be found.

*E-mail: duartefontes@tecnico.ulisboa.pt

†E-mail: jorge.romao@tecnico.ulisboa.pt

‡E-mail: rasantos@fc.ul.pt

§E-mail: jpsilva@cftp.ist.utl.pt

1 Introduction

As proposed in [2], CP-violation in the scalar sector can be found in the interactions with gauge bosons in a very simple way. If CP were conserved, any decay $h_i \to h_j Z$ would imply opposite CP parities for h_i and h_j. Moreover, assuming only lagrangian terms up to dimension four, any scalar h_i decaying into ZZ would be CP even [1]. Thus, for example, the simultaneous presence of the decays $h_3 \to h_2 Z$, $h_2 \to h_1 Z$, and $h_3 \to h_1 Z$ violates CP. We say that points in the C2HDM parameter space which lead to this situation belong to class C_1. Similarly (with the caveat in footnote 1), the simultaneous presence of the decays $h_i \to h_j Z$, $h_i \to ZZ$, and $h_j \to ZZ$, also violates CP. Within the 2HDM, there are three such possibilities, according to the (i, j) assignments, which we name classes C_2, C_3, and C_4. Notice that classes C_1-C_4 represent CP-violation, regardless of the origin of the neutral scalars. They may come from an N Higgs doublet model, or indeed from scalar fields in any number and from any representation of $SU(2)_L$ (singlets, doublets, triplets, combinations thereof, etc...) In Table 1, we show the decays involved in each class. Furthermore,

Classes	C_1	C_2	C_3	C_4	C_5
Decays	$h_3 \to h_2 Z$	$h_2 \to h_1 Z$	$h_3 \to h_1 Z$	$h_3 \to h_2 Z$	$h_3 \to ZZ$
	$h_2 \to h_1 Z$	$h_1 \to ZZ$	$h_1 \to ZZ$	$h_2 \to ZZ$	$h_2 \to ZZ$
	$h_3 \to h_1 Z$	$h_2 \to ZZ$	$h_3 \to ZZ$	$h_3 \to ZZ$	$h_1 \to ZZ$

Table 1: Classes of combined measurements guaranteed to probe CP-violation in 2HDMs.

in the specific context of a 2HDM, the properties of the fields ensure that, if CP were conserved, there would be two CP even neutral scalars and one CP odd neutral scalar, usually denoted by H, h, and A, respectively. Thus, in the 2HDM, the simultaneous presence of $h_i \to ZZ$ for $i = 1, 2, 3$ signals CP-violation. We denote that possibility by class C_5. We stress that class C_5 does not represent necessarily CP-violation in models other than the 2HDM. For example, even with three Higgs doublets one will surely have three neutral scalars and class C_5 would be consistent with CP-conservation. We will further discuss other classes that probe CP-violation that involve one scalar to two scalar decays that usually have the drawback of having smaller cross sections.

One of the most interesting points of our proposal is that although the above described classes constitute a sign of CP-violation, they have all been searched for individually at run 1. In fact, the searches $h_i \to ZZ$ and $h_i \to h_j Z$ were already performed by both the ATLAS and CMS collaborations. Therefore, as long as we have enough signal events in three of the proposed channels for a given set of parameters, there are good chances of observing direct CP-violation at the next LHC run.

2 The complex two-Higgs doublet model

We use as a benchmark model an extension of the SM with an extra scalar doublet. This complex 2HDM, first proposed in [4], has a softly broken Z_2 symmetry $\phi_1 \to \phi_1, \phi_2 \to -\phi_2$ and the scalar

[1] There are CP conserving terms of dimension higher than four that can mediate the decay of a pseudoscalar into two vector bosons. Those could appear at loop level from a fundamental theory, but would lead to rates far smaller than the tree level rates considered in this note. A calculation performed in the framework of the 2HDM has shown [3] that the loop mediated decays of the type $h_i \to ZZ$ are several orders of magnitude smaller than the tree-level ones.

potential is written as [5]

$$
\begin{aligned}
V_H &= m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2\, \phi_1^\dagger\phi_2 - (m_{12}^2)^*\, \phi_2^\dagger\phi_1 \\
&+ \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4\, (\phi_1^\dagger\phi_2)\, (\phi_2^\dagger\phi_1) \\
&+ \frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \frac{\lambda_5^*}{2}(\phi_2^\dagger\phi_1)^2\,, \qquad (1)
\end{aligned}
$$

and because the potential has to be hermitian, all couplings except m_{12}^2 and λ_5 are real. In order to assure that the two phases cannot be removed simultaneously, we impose $\arg(\lambda_5) \neq 2\arg(m_{12}^2)$ [4]. By taking m_{12}^2 and λ_5 real we recover the corresponding CP-conserving 2HDM.

The model has three neutral particles with no definite CP, h_1, h_2 and h_3, and two charged scalars $H^\pm$. The mass matrix of the neutral scalar states is obtained via the rotation matrix [6]

$$
R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} \qquad (2)
$$

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

$$
-\pi/2 < \alpha_1 \leq \pi/2, \qquad -\pi/2 < \alpha_2 \leq \pi/2, \qquad -\pi/2 \leq \alpha_3 \leq \pi/2. \qquad (3)
$$

The C2HDM has 9 independent parameters which we choose to be v, $\tan\beta$, $m_{H^\pm}$, α_1, α_2, α_3, m_1, m_2, and $\mathrm{Re}(m_{12}^2)$. With this choice the mass of heavier neutral scalar is a dependent parameter given by

$$
m_3^2 = \frac{m_1^2\, R_{13}(R_{12}\tan\beta - R_{11}) + m_2^2\; R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}. \qquad (4)
$$

and the parameter space will be restricted to values which obey $m_3 > m_2$.

We will analyse the usual four Yukawa versions of the C2HDM, in which the Z_2 symmetry is extended to the Yukawa Lagrangian [7] in order to avoid flavour changing neutral currents (FCNC). In all models the up-type quarks couple to ϕ_2 and the so-called Type I (Type II) is obtained by coupling down-type quarks and charged leptons to ϕ_2 (ϕ_1), while by coupling the down-type quarks to ϕ_1 and the charged leptons to ϕ_2 we obtain the Flipped model and by coupling the down-type quarks to ϕ_2 and the charged leptons to ϕ_1 we obtain the Lepton Specific (LS) model.

The allowed parameter space of the C2HDM was recently reviewed in [8] (details and references in [8]). The benchmark points that clearly signal CP-violation will be presented in the next section and are chosen from this set.

3 Benchmarks

In this section, we present some benchmark points that allow us to definitely probe CP-violation during LHC's run 2. In table 2, we present four benchmark points, where the first three are for Type II and $P4$ is for the Flipped model. For each point we give the values of the parameters of the model, the values of the pseudoscalar component of the Yukawa coupling of the lightest Higgs and the values of the cross sections for the different processes. The cross sections are calculated assuming that all scalars in the final state are detected in the decay to $b\bar{b}$ and all Z bosons are

	$P1$	$P2$	$P3$	$P4$
α_1	1.12569	1.04842	-1.33589	1.41610
α_2	0.49091	-0.00825	-0.00129	0.24037
α_3	-1.56775	0.00674	0.63749	-0.81993
β	0.92913	1.00182	1.27669	1.29413
$\tan\beta$	1.33845	1.56366	3.30155	3.52171
m_1 (GeV)	125.00	125.00	125.00	125.00
m_2 (GeV)	127.32	273.15	282.53	231.74
m_3 (GeV)	252.63	421.64	287.80	360.59
$m_{H^\pm}$ (GeV)	481.25	452.50	604.89	527.67
$\text{Re}(m_{12}^2)$ (GeV)^2	-0.5625E+02	0.1183E+05	0.1590E+05	0.2156E+05
b_{D_1}	-0.63099	0.01291	0.00426	-0.83837
b_{L_1}	-0.63099	0.01291	0.00426	0.06760
C_1[1] $\sigma_3\times\text{BR}(h_3 \to h_2 Z \to b\bar{b}l\bar{l})$	114.528 [fb]	61.529 [fb]	0.000 [fb]	27.484 [fb]
C_1[2] $\sigma_2\times\text{BR}(h_2 \to h_1 Z \to b\bar{b}l\bar{l})$	0.000 [fb]	0.615 [fb]	7.401 [fb]	18.462 [fb]
C_1[3] $\sigma_3\times\text{BR}(h_3 \to h_1 Z \to b\bar{b}l\bar{l})$	26.656 [fb]	1.100 [fb]	24.519 [fb]	1.787 [fb]
C_2[1] $\sigma_2\times\text{BR}(h_2 \to h_1 Z \to b\bar{b}l\bar{l})$	0.000 [fb]	0.615 [fb]	7.401 [fb]	18.462 [fb]
C_2[2] $\sigma_1\times\text{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495 [fb]	5.792 [fb]	5.592 [fb]	4.802 [fb]
C_2[3] $\sigma_2\times\text{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386 [fb]	2.598 [fb]	1.802 [fb]	1.220 [fb]
C_3[1] $\sigma_3\times\text{BR}(h_3 \to h_1 Z \to b\bar{b}l\bar{l})$	26.656 [fb]	1.100 [fb]	24.519 [fb]	1.787 [fb]
C_3[2] $\sigma_1\times\text{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495 [fb]	5.792 [fb]	5.592 [fb]	4.802 [fb]
C_3[3] $\sigma_3\times\text{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011 [fb]	0.003 [fb]	1.733 [fb]	1.058 [fb]
C_4[1] $\sigma_3\times\text{BR}(h_3 \to h_2 Z \to b\bar{b}l\bar{l})$	114.528 [fb]	61.529 [fb]	0.000 [fb]	27.484 [fb]
C_4[2] $\sigma_2\times\text{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386 [fb]	2.598 [fb]	1.802 [fb]	1.220 [fb]
C_4[3] $\sigma_3\times\text{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011 [fb]	0.003 [fb]	1.733 [fb]	1.058 [fb]
C_5[1] $\sigma_3\times\text{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011 [fb]	0.003 [fb]	1.733 [fb]	1.058 [fb]
C_5[2] $\sigma_2\times\text{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386 [fb]	2.598 [fb]	1.802 [fb]	1.220 [fb]
C_5[3] $\sigma_1\times\text{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495 [fb]	5.792 [fb]	5.592 [fb]	4.802 [fb]

Table 2: Benchmark points for Type II: $P1$, $P2$ and $P3$, and for the Flipped model: $P4$, for LHC at $\sqrt{s} = 13$ TeV. All Z bosons decay leptonically which corresponds to a factor of 0.06732 for each Z decay.

detected in the leptonic decays, providing therefore a very conservative estimate for the number of signal events available. Regarding the cross sections, we sum over all possible production process with one scalar in the final state. Therefore, the numbers presented in the table correspond either to

$$\sigma(pp \to h_i + X)\, BR(h_i \to h_j Z)\, BR(h_j \to b\bar{b})\, BR(Z \to ll)\,, \tag{5}$$

or

$$\sigma(pp \to h_i + X)\, BR(h_i \to ZZ)\, BR^2(Z \to ll) \tag{6}$$

and $l = e,\, \mu$.

The general criteria for the choice of our benchmark points is the following: the points have passed all relevant experimental and theoretical constraints described in detail in [1]; the number of events for a luminosity of $100 fb^{-1}$ should be at least above 50, and the smallest number in table 2 for this luminosity is 61 events. Note that this number already takes into account the decay of the scalar into $b\bar{b}$ and the decay of all Z bosons into leptons (a reduction of 0.06732 for each Z). Therefore, we expect a much larger number of events when all other combinations of final states are taken into account by the experiments (as it is obviously the case for the ZZ final states, where we can have combinations of leptons and jets final states). In table 3 we show the rates obtained

	$P1$	$P2$	$P3$	$P4$
$\mu_{WW}(h_1) = \mu_{ZZ}(h_1)$	1.09016	1.14962	1.11696	0.95402
$\mu_{\tau\tau}(h_1)$	1.16717	0.98826	0.96621	1.02628
$\mu_{\gamma\gamma}(h_1)$	0.92139	1.02589	0.87922	0.85345
$\mu_{bb(VH)}(h_1)$	0.71662	0.93593	0.65922	0.94294
$\mu_{WW}(h_2)/\mu_{WW}^{\rm exp}$	0.225/NA	0.151/0.185	0.117/0.170	0.058/0.121
$\mu_{ZZ}(h_2)/\mu_{ZZ}^{\rm exp}$	0.225/1.264	0.151/0.190	0.117/0.176	0.058/0.130
$\mu_{\tau\tau}(h_2)/\mu_{\tau\tau}^{\rm exp}$	1.59/ 3.98	180.00/ 472.37	7.98/ 490.42	0.90/ 363.88
$\sigma BR_{\gamma\gamma}(h_2)/\sigma BR_{\gamma\gamma}^{\rm exp}$ [fb]	15.265/ 29.705	0.318/2.678	0.011/2.727	0.018/5.998
$\mu_{\gamma\gamma}(h_2)/\mu_{\gamma\gamma}^{\rm exp}$ ($m < 150$GeV)	0.258/0.259	0.000/0.000	0.000/0.000	0.000/0.000
$\sigma BR_{Zh\to Zbb}(h_2)/\sigma BR_{Zh\to Zbb}^{\rm exp}$ [pb]	0.000/ 0.000	0.003/0.308	0.042/0.250	0.108/0.403
$\sigma BR_{Zh\to Z\tau\tau}(h_2)/\sigma BR_{Zh\to Z\tau\tau}^{\rm exp}$ [pb]	0.000/ 0.000	0.000/0.105	0.005/0.089	0.012/0.085
$\sigma BR_{Zh\to llbb}(h_2)/\sigma BR_{Zh\to llbb}^{\rm exp}$ [fb]	0.000/0.000	0.222/ 15.242	2.855/ 12.167	7.259/ 14.082
$\mu_{WW}(h_3)/\mu_{WW}^{\rm exp}$	0.053/0.074	0.000/0.083	0.111/0.125	0.072/0.099
$\mu_{ZZ}(h_3)/\mu_{ZZ}^{\rm exp}$	0.053/0.068	0.000/0.086	0.111/0.147	0.072/0.095
$\mu_{\tau\tau}(h_3)/\mu_{\tau\tau}^{\rm exp}$	3.12/ 427.59	8.70/ 1241.83	13.52/ 500.43	0.04/ 663.64
$\sigma BR_{\gamma\gamma}(h_3)/\sigma BR_{\gamma\gamma}^{\rm exp}$ [fb]	0.022/6.511	0.028/2.002	0.010/2.672	0.004/2.823
$\sigma BR_{Zh\to Zbb}(h_3)/\sigma BR_{Zh\to Zbb}^{\rm exp}$ [pb]	0.147/0.310	0.005/0.081	0.135/0.228	0.009/0.156
$\sigma BR_{Zh\to Z\tau\tau}(h_3)/\sigma BR_{Zh\to Z\tau\tau}^{\rm exp}$ [pb]	0.017/0.102	0.001/0.035	0.016/0.081	0.001/0.038
$\sigma BR_{Zh\to llbb}(h_3)/\sigma BR_{Zh\to llbb}^{\rm exp}$ [fb]	9.926/ 23.839	0.337/2.731	9.076/ 15.230	0.605/7.358

Table 3: Constraints from the LHC at $\sqrt{s} = 8$ TeV for the benchmark points $P1$, $P2$ and $P3$ (Type II) and $P4$ (Flipped). NA stands for not available.

for the benchmark points which are then compared to the available experimental data from the LHC at $\sqrt{s} = 8$ TeV.

The criteria for the choice of each particular point is severely constrained by the ACME [9] results. In fact, all the points have similar features in that they either have two neutral scalar masses almost degenerate or values of the angles very close to zero (therefore approaching the limit of the CP-conserving 2HDM). Points $P1$ and $P3$ have degenerate masses while point $P2$ has very small α_2 and α_3 values. That is why for point $P2$, the decay $h_2 \to h_1 Z$ is suppressed. In the limit $\alpha_2 = \alpha_3 = 0$, h_3 is the pseudo-scalar and h_1 and h_2 are scalars and $h_2 \to h_1 Z$ is forbidden. For the same reason, $h_3 \to ZZ$ is forbidden. Note however that although α_2 and α_3 are very small we still have a large number of signal events for $100 fb^{-1}$ in $h_2 \to h_1 Z$. As $\alpha_{2,3}$ move away from zero (the CP-conserving limit) certain CP-violating observables grow extremely fast. Thus, we can be very close to this limit and still have large CP-violating signals.

The points were also chosen so that they would probe more than one class simultaneously. $P1$ probes classes C_3, C_4 and C_5; $P2$ probes C_1 and C_2; $P3$ probes C_2, C_3 and C_5 while the point for the Flipped model probes all classes. Furthermore, points $P1$ and $P4$ were also chosen to show that large pseudoscalar components are not only still allowed, as previously discussed in [8], but they can also easily be probed at the next LHC run.

In table 4 we present the production cross sections for h_1, h_2 and h_3. In the same table we show the $\sigma(h_i) \times Br(h_i \to X)$ where X stands for the main final sates being searched by ATLAS and CMS at the next LHC run. These numbers allow the experimental groups to understand if a

	$P1$	$P2$	$P3$	$P4$
$\sigma(h_1)$ **13TeV**	61.600 [pb]	53.217 [pb]	54.825 [pb]	51.275 [pb]
$\sigma(h_1)\text{BR}(h_1 \to W^*W^*)$	11.819 [pb]	12.459 [pb]	12.028 [pb]	10.328 [pb]
$\sigma(h_1)\text{BR}(h_1 \to Z^*Z^*)$	1.212 [pb]	1.278 [pb]	1.234 [pb]	1.060 [pb]
$\sigma(h_1)\text{BR}(h_1 \to bb)$	34.383 [pb]	29.087 [pb]	28.256 [pb]	30.313 [pb]
$\sigma(h_1)\text{BR}(h_1 \to \tau\tau)$	3.969 [pb]	3.360 [pb]	3.264 [pb]	3.485 [pb]
$\sigma(h_1)\text{BR}(h_1 \to \gamma\gamma)$	129.973 [fb]	144.664 [fb]	123.188 [fb]	120.222 [fb]
$\sigma_2 \equiv \sigma(h_2)$ **13TeV**	56.583 [pb]	4.262 [pb]	1.602 [pb]	3.354 [pb]
$\sigma_2 \times \text{BR}(h_2 \to WW)$	2.814 [pb]	1.323 [pb]	0.910 [pb]	0.656 [pb]
$\sigma_2 \times \text{BR}(h_2 \to ZZ)$	0.306 [pb]	0.573 [pb]	0.398 [pb]	0.269 [pb]
$\sigma_2 \times \text{BR}(h_2 \to bb)$	42.534 [pb]	1.894 [pb]	0.067 [pb]	1.944 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \tau\tau)$	4.911 [pb]	0.224 [pb]	0.008 [pb]	0.002 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \gamma\gamma)$	35.041 [fb]	0.879 [fb]	0.027 [fb]	0.046 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z)$	0.000 [pb]	0.017 [pb]	0.213 [pb]	0.464 [pb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z \to bbZ)$	0.000 [pb]	0.009 [pb]	0.110 [pb]	0.274 [pb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z \to \tau\tau Z)$	0.000 [fb]	1.055 [fb]	12.697 [fb]	31.530 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1)$	0.000 [fb]	0.007 [fb]	5.016 [fb]	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bb\, bb)$	0.000 [fb]	0.002 [fb]	1.332 [fb]	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bb\, \tau\tau)$	0.000 [fb]	0.000 [fb]	0.308 [fb]	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to \tau\tau\, \tau\tau)$	0.000 [fb]	0.000 [fb]	0.018 [fb]	0.000 [fb]
$\sigma_3 \equiv \sigma(h_3)$ **13TeV**	4.043 [pb]	8.480 [pb]	2.086 [pb]	1.819 [pb]
$\sigma_3 \times \text{BR}(h_3 \to WW)$	0.526 [pb]	0.001 [pb]	0.871 [pb]	0.509 [pb]
$\sigma_3 \times \text{BR}(h_3 \to ZZ)$	0.223 [pb]	0.001 [pb]	0.382 [pb]	0.233 [pb]
$\sigma_3 \times \text{BR}(h_3 \to bb)$	0.047 [pb]	0.016 [pb]	0.109 [pb]	0.058 [pb]
$\sigma_3 \times \text{BR}(h_3 \to \tau\tau)$	5.558 [fb]	1.913 [fb]	12.856 [fb]	0.020 [fb]
$\sigma_3 \times \text{BR}(h_3 \to \gamma\gamma)$	0.059 [fb]	0.093 [fb]	0.028 [fb]	0.013 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z)$	0.709 [pb]	0.030 [pb]	0.707 [pb]	0.045 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z \to bbZ)$	0.396 [pb]	0.016 [pb]	0.364 [pb]	0.027 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z \to \tau\tau Z)$	45.708 [fb]	1.887 [fb]	42.067 [fb]	3.051 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z)$	2.263 [pb]	2.057 [pb]	0.000 [pb]	0.705 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z \to bbZ)$	1.701 [pb]	0.914 [pb]	0.000 [pb]	0.408 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z \to \tau\tau Z)$	196.416 [fb]	107.996 [fb]	0.000 [fb]	0.500 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1)$	0.090 [fb]	0.230 [fb]	2.071 [fb]	19.918 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bb\, bb)$	0.028 [fb]	0.069 [fb]	0.550 [fb]	6.961 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bb\, \tau\tau)$	0.007 [fb]	0.016 [fb]	0.127 [fb]	1.601 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to \tau\tau\, \tau\tau)$	0.000 [fb]	0.001 [fb]	0.007 [fb]	0.092 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1)$	263.916 [fb]	0.038 [fb]	0.000 [fb]	11.157 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to bb\, bb)$	110.732 [fb]	0.009 [fb]	0.000 [fb]	3.822 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to bb\, \tau\tau)$	25.567 [fb]	0.002 [fb]	0.000 [fb]	0.444 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to \tau\tau\, \tau\tau)$	1.476 [fb]	0.000 [fb]	0.000 [fb]	0.001 [fb]

Table 4: Predictions for $\sigma \times \text{BR}$ for the LHC at $\sqrt{s} = 13$ TeV for the benchmark points $P1$, $P2$ and $P3$ (Type II) and $P4$ (Flipped).

given scalar is found in direct production whether it comes from a CP-violating process or not. In the same table we also present the values of the scalar production cross sections that lead to decays of the type $h_i \to h_j h_j$ and $h_i \to h_j h_k$ and that are clearly too small to be detected at the LHC for the sets of benchmark chosen, except for a few cases for points $P1$ and $P4$.

In table 5 we present the values of the parameters and the cross sections for benchmark point $P5$ in Type I and $P6$ for the LS model. In Type I it was possible to find a point that not only complies with all the constraints but that probes all CP-violating classes at the same time. For the LS model the classes probed are C_2, C_3 and C_5.

	$P5$	$P6$
α_1	1.30680	1.08742
α_2	0.10867	0.00960
α_3	-0.20624	-0.41962
β	1.15333	1.03051
$\tan\beta$	2.25459	1.66717
m_1 (GeV)	125.00	125.00
m_2 (GeV)	235.45	262.98
m_3 (GeV)	359.20	264.60
$m_{H^\pm}$ (GeV)	522.87	471.76
$\mathrm{Re}(m_{12}^2)$ (GeV)^2	0.9504E+02	-0.3006E+05
b_{D_1}	0.04810	0.00576
b_{L_1}	0.04810	-0.01600
C_1**[1]** $\sigma_3\times\mathrm{BR}(h_3 \to h_2 Z \to b\bar{b}l\bar{l})$	1.251 [fb]	0.000 [fb]
C_1**[2]** $\sigma_2\times\mathrm{BR}(h_2 \to h_1 Z \to b\bar{b}l\bar{l})$	5.644 [fb]	3.030 [fb]
C_1**[3]** $\sigma_3\times\mathrm{BR}(h_3 \to h_1 Z \to b\bar{b}l\bar{l})$	15.477 [fb]	27.984 [fb]
C_2**[1]** $\sigma_2\times\mathrm{BR}(h_2 \to h_1 Z \to b\bar{b}l\bar{l})$	5.644 [fb]	3.030 [fb]
C_2**[2]** $\sigma_1\times\mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	4.954 [fb]	5.146 [fb]
C_2**[3]** $\sigma_2\times\mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.934 [fb]	1.053 [fb]
C_3**[1]** $\sigma_3\times\mathrm{BR}(h_3 \to h_1 Z \to b\bar{b}l\bar{l})$	15.477 [fb]	27.984 [fb]
C_3**[2]** $\sigma_1\times\mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	4.954 [fb]	5.146 [fb]
C_3**[3]** $\sigma_3\times\mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.326 [fb]	1.840 [fb]
C_4**[1]** $\sigma_3\times\mathrm{BR}(h_3 \to h_2 Z \to b\bar{b}l\bar{l})$	1.251 [fb]	0.000 [fb]
C_4**[2]** $\sigma_2\times\mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.934 [fb]	1.053 [fb]
C_4**[3]** $\sigma_3\times\mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.326 [fb]	1.840 [fb]
C_5**[1]** $\sigma_3\times\mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.326 [fb]	1.840 [fb]
C_5**[2]** $\sigma_2\times\mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.934 [fb]	1.053 [fb]
C_5**[3]** $\sigma_1\times\mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	4.954 [fb]	5.146 [fb]

Table 5: Benchmark points for Type I: $P5$ and for the LS model: $P6$, for LHC at $\sqrt{s} = 13$ TeV. All Z decay leptonically corresponding to a factor of 0.06732.

As we did for the remaining benchmark points, we present in table 6 the effect of the LHC constraints on the processes involving scalars. In table 7 we present the production cross sections for h_1, h_2 and h_3 and also the $\sigma(h_i) \times Br(h_i \to X)$ where again X stands for the most relevant final states searched by ATLAS and CMS at the next LHC run. We also show the values of the scalar production cross sections that lead to decays of the type $h_i \to h_j h_j$ and $h_i \to h_j h_k$. Interestingly, for the benchmark points of Type I and LS, there are many scalar to scalar decays that could be probed at the next LHC run.

References

[1] D. Fontes, J. C. Romão, R. Santos and J. P. Silva, arXiv:1506.06755 [hep-ph].

	$P5$	$P6$
$\mu_{WW}(h_1) = \mu_{ZZ}(h_1)$	0.98240	1.02070
$\mu_{\tau\tau}(h_1)$	1.12419	0.83628
$\mu_{\gamma\gamma}(h_1)$	0.84875	0.86872
$\mu_{bb(VH)}(h_1)$	0.99480	1.02881
$\mu_{WW}(h_2)/\mu_{WW}^{\rm exp}$	0.091/0.115	0.058/0.108
$\mu_{ZZ}(h_2)/\mu_{ZZ}^{\rm exp}$	0.091/0.111	0.058/0.112
$\mu_{\tau\tau}(h_2)/\mu_{\tau\tau}^{\rm exp}$	0.56/ 377.80	72.97/ 451.42
$\sigma BR_{\gamma\gamma}(h_2)/\sigma BR_{\gamma\gamma}^{\rm exp}$ [fb]	0.046/3.975	0.125/6.838
$\mu_{\gamma\gamma}(h_2)/\mu_{\gamma\gamma}^{\rm exp}$ ($m < 150$GeV)	0.000/0.000	0.000/0.000
$\sigma BR_{Zh\to Zbb}(h_2)/\sigma BR_{Zh\to Zbb}^{\rm exp}$ [pb]	0.032/0.337	0.016/0.349
$\sigma BR_{Zh\to Z\tau\tau}(h_2)/\sigma BR_{Zh\to Z\tau\tau}^{\rm exp}$ [pb]	0.004/0.080	0.001/0.114
$\sigma BR_{Zh\to llbb}(h_2)/\sigma BR_{Zh\to llbb}^{\rm exp}$ [fb]	2.127/ 13.013	1.100/ 27.341
$\mu_{WW}(h_3)/\mu_{WW}^{\rm exp}$	0.087/0.097	0.102/0.113
$\mu_{ZZ}(h_3)/\mu_{ZZ}^{\rm exp}$	0.087/0.094	0.102/0.123
$\mu_{\tau\tau}(h_3)/\mu_{\tau\tau}^{\rm exp}$	0.89/ 656.23	281.79/ 454.89
$\sigma BR_{\gamma\gamma}(h_3)/\sigma BR_{\gamma\gamma}^{\rm exp}$ [fb]	0.046/2.758	0.875/6.334
$\sigma BR_{Zh\to Zbb}(h_3)/\sigma BR_{Zh\to Zbb}^{\rm exp}$ [pb]	0.075/0.155	0.151/0.348
$\sigma BR_{Zh\to Z\tau\tau}(h_3)/\sigma BR_{Zh\to Z\tau\tau}^{\rm exp}$ [pb]	0.009/0.038	0.013/0.114
$\sigma BR_{Zh\to llbb}(h_3)/\sigma BR_{Zh\to llbb}^{\rm exp}$ [fb]	5.077/7.483	10.163/ 24.919

Table 6: Constraints from the LHC at $\sqrt{s} = 8$ TeV for the benchmark points $P5$ (Type I) and $P6$ (LS).

[2] G. C. Branco, L. Lavoura and J. P. Silva, "CP Violation", Int. Ser. Monogr. Phys. **103** (1999) 1. See, in particular, section 22.9.3.

[3] A. Arhrib and R. Benbrik, hep-ph/0610184.

[4] I. F. Ginzburg, M. Krawczyk and P. Osland, *Two Higgs doublet models with CP violation*, hep-ph/0211371.

[5] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rept.* **516** (2012) 1 [arXiv:1106.0034 [hep-ph]].

[6] A. W. El Kaffas, P. Osland and O. M. Ogreid, *CP violation, stability and unitarity of the two Higgs doublet model*, *Nonlin. Phenom. Complex Syst.* **10**(2007) 347 [hep-ph/0702097].

[7] S.L. Glashow and S. Weinberg, Phys. Rev. D **15**, 1958 (1977); E.A. Paschos, Phys. Rev. D **15**, 1966 (1977).

[8] D. Fontes, J. C. Romo, R. Santos and J. P. Silva, JHEP **1506**, 060 (2015) [arXiv:1502.01720 [hep-ph]].

[9] J. Baron *et al.* [ACME Collaboration], Science **343**, 269 (2014) [arXiv:1310.7534 [physics.atom-ph]].

	$P5$	$P6$
$\sigma(h_1)$ **13TeV**	55.144 [pb]	53.455 [pb]
$\sigma(h_1)\text{BR}(h_1 \to W^*W^*)$	10.657 [pb]	11.069 [pb]
$\sigma(h_1)\text{BR}(h_1 \to Z^*Z^*)$	1.093 [pb]	1.136 [pb]
$\sigma(h_1)\text{BR}(h_1 \to bb)$	33.118 [pb]	32.152 [pb]
$\sigma(h_1)\text{BR}(h_1 \to \tau\tau)$	3.825 [pb]	2.845 [pb]
$\sigma(h_1)\text{BR}(h_1 \to \gamma\gamma)$	119.794 [fb]	122.579 [fb]
$\sigma_2 \equiv \sigma(h_2)$ **13TeV**	1.620 [pb]	4.920 [pb]
$\sigma_2{\times}\text{BR}(h_2 \to WW)$	1.032 [pb]	0.542 [pb]
$\sigma_2{\times}\text{BR}(h_2 \to ZZ)$	0.427 [pb]	0.232 [pb]
$\sigma_2{\times}\text{BR}(h_2 \to bb)$	0.012 [pb]	0.097 [pb]
$\sigma_2{\times}\text{BR}(h_2 \to \tau\tau)$	0.001 [pb]	0.109 [pb]
$\sigma_2{\times}\text{BR}(h_2 \to \gamma\gamma)$	0.123 [fb]	0.344 [fb]
$\sigma_2{\times}\text{BR}(h_2 \to h_1 Z)$	0.140 [pb]	0.075 [pb]
$\sigma_2{\times}\text{BR}(h_2 \to h_1 Z \to bbZ)$	0.084 [pb]	0.045 [pb]
$\sigma_2{\times}\text{BR}(h_2 \to h_1 Z \to \tau\tau Z)$	9.683 [fb]	3.982 [fb]
$\sigma_2{\times}\text{BR}(h_2 \to h_1 h_1)$	0.000 [fb]	3772.577 [fb]
$\sigma_2{\times}\text{BR}(h_2 \to h_1 h_1 \to bb\ bb)$	0.000 [fb]	1364.787 [fb]
$\sigma_2{\times}\text{BR}(h_2 \to h_1 h_1 \to bb\ \tau\tau)$	0.000 [fb]	241.505 [fb]
$\sigma_2{\times}\text{BR}(h_2 \to h_1 h_1 \to \tau\tau\ \tau\tau)$	0.000 [fb]	10.684 [fb]
$\sigma_3 \equiv \sigma(h_3)$ **13TeV**	9.442 [pb]	10.525 [pb]
$\sigma_3{\times}\text{BR}(h_3 \to WW)$	0.638 [pb]	0.945 [pb]
$\sigma_3{\times}\text{BR}(h_3 \to ZZ)$	0.293 [pb]	0.406 [pb]
$\sigma_3{\times}\text{BR}(h_3 \to bb)$	0.004 [pb]	0.422 [pb]
$\sigma_3{\times}\text{BR}(h_3 \to \tau\tau)$	0.432 [fb]	407.337 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to \gamma\gamma)$	0.140 [fb]	2.410 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_1 Z)$	0.383 [pb]	0.691 [pb]
$\sigma_3{\times}\text{BR}(h_3 \to h_1 Z \to bbZ)$	0.230 [pb]	0.416 [pb]
$\sigma_3{\times}\text{BR}(h_3 \to h_1 Z \to \tau\tau Z)$	26.554 [fb]	36.779 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_2 Z)$	2.495 [pb]	0.000 [pb]
$\sigma_3{\times}\text{BR}(h_3 \to h_2 Z \to bbZ)$	0.019 [pb]	0.000 [pb]
$\sigma_3{\times}\text{BR}(h_3 \to h_2 Z \to \tau\tau Z)$	2.188 [fb]	0.000 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_1 h_1)$	433.402 [fb]	6893.255 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_1 h_1 \to bb\ bb)$	156.329 [fb]	2493.740 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_1 h_1 \to bb\ \tau\tau)$	36.111 [fb]	441.277 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_1 h_1 \to \tau\tau\ \tau\tau)$	2.085 [fb]	19.521 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_2 h_1)$	0.000 [fb]	0.000 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_2 h_1 \to bb\ bb)$	0.000 [fb]	0.000 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_2 h_1 \to bb\ \tau\tau)$	0.000 [fb]	0.000 [fb]
$\sigma_3{\times}\text{BR}(h_3 \to h_2 h_1 \to \tau\tau\ \tau\tau)$	0.000 [fb]	0.000 [fb]

Table 7: Predictions for $\sigma \times \text{BR}$ at $\sqrt{s} = 13$ TeV for the benchmark points $P5$ (Type I) and $P6$ (LS).