Phenomenological LHC Benchmarks for the $\mathcal{CP}$-conserving Two-Higgs-Doublet Model

Howard E. Haber* and Oscar Stål†

In this note we present briefly our proposal for benchmark scenarios in the CP-conserving two-Higgs-doublet Model (2HDM), following the call by the LHC Higgs cross section working group. The scenarios we propose are obtained in a purely phenomenological approach, similiar to the well-known benchmark scenarios [1] that are in wide use for the MSSM. This means that we have selected scenarios to capture particular features of the model, such as important decay channels. Our hope is that these scenarios will be useful for interpretation of 2HDM searches at LHC run-II.

1 The hybrid basis

Based on the work of [2, 3], we propose a "hybrid" strategy for specifying the input parameters for the softly-broken $\mathbb{Z}_2$-invariant 2HDM. Both Type-I and Type-II Higgs-fermion Yukawa couplings are considered. The masses of the physical $\mathcal{CP}$-even Higgs scalars are given directly as input parameters together with $\cos(\beta-\alpha)$, which determines the phenomenologically important couplings of the $\mathcal{CP}$-even scalars to the $W^\pm$ and Z bosons, and $\tan\beta$ which specifies the basis of scalar fields where the discrete symmetry of the Higgs-fermion Yukawa interactions is manifest. In addition, we specify the real Higgs basis self-coupling coefficients Z_4, Z_5, and Z_7 as input parameters. We henceforth designate the input parameter set $\{m_h, m_H, \cos(\beta-\alpha), \tan\beta, Z_4, Z_5, Z_7\}$ as the hybrid basis of parameters as indicated in Table 1. Furthermore, we employ the conventions, $0 \le \sin(\beta-\alpha) \le 1$ and $\tan\beta$ non-negative. In this convention $\cos(\beta-\alpha)$ can take on either sign.

Parameter	Description
m_h	Mass of the light $\mathcal{CP}$-even Higgs boson
m_H	Mass of the heavy $\mathcal{CP}$-even Higgs boson
$c_{\beta-\alpha}$	Basis pseudo-invariant quantity $\cos(\beta-\alpha)$ (entering the HW^+W^- and HZZ couplings)
$\tan\beta$	Ratio of vacuum expectation values in the basis with $\lambda_6=\lambda_7=0$ (manifest $\mathbb{Z}_2$ symmetry)
Z_4, Z_5, Z_7	Quartic scalar couplings in the Higgs basis of $\mathcal{O}(1)$

Table 1: 2HDM input parameters in the hybrid basis.

Using these input parameters, the remaining physical masses (m_A and $m_{H^\pm}$) can be determined from Z_4 and Z_5. The mass spectrum is independent of Z_7, which only enters in Higgs self-interactions. One may also compute the remaining self-coupling coefficients Z_1, Z_2, Z_3 and Z_6 [2]. In order to ensure that these remain of $\mathcal{O}(1)$, one should choose the input parameters m_H and $c_{\beta-\alpha}$ such that $m_H^2 c_{\beta-\alpha}/v^2 \lesssim \mathcal{O}(1)$. The masses of the $\mathcal{CP}$-odd Higgs and charged Higgs scalar are given by

$$m_A^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - Z_5 v^2\,, \tag{1}$$

$$m_{H^\pm}^2 = m_A^2 - \tfrac{1}{2}(Z_4 - Z_5)v^2\,. \tag{2}$$

*Electronic address: haber@scipp.ucsc.edu
†Electronic address: oscar.stal@fysik.su.se

One can also determine the off-diagonal squared-mass parameter of the generic basis, m_{12}^2, from

$$m_{12}^2 = \left[m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 + \tfrac{1}{2}\tan 2\beta (Z_6 - Z_7)v^2\right]\sin\beta\cos\beta\,, \tag{3}$$

where $Z_6 v^2 = (m_h^2 - m_H^2)s_{\beta-\alpha}c_{\beta-\alpha}$. This parameter softly breaks the $\mathbb{Z}_2$ symmetry.

In practice, taking the parameters Z_4 and Z_5 as input parameters is not very intuitive. Clearly a more physical approach is to take m_A and $m_{H^\pm}$ as input parameter and then compute Z_4 and Z_5 using eqs. (1) and (2). The danger with such an approach is that a poor choice of m_A and $m_{H^\pm}$ will yield values of Z_4 and Z_5 that violate unitarity constraints. We therefore employ our hybrid basis to perform parameter scans. To reduce the number of free parameters, we sometimes introduce simplifying assumptions in the definition of a given scenario. The following two special cases are noteworthy:

$$m_A = m_{H^\pm} \quad\Longleftrightarrow\quad Z_4 = Z_5\,, \tag{4}$$

$$m_H = m_{H^\pm} \text{ and } c_{\beta-\alpha} = 0 \quad\Longrightarrow\quad Z_4 = -Z_5\,. \tag{5}$$

Parameters for the identified benchmark scenarios can, if necesssary, be translated to the basis of physical parameters using the above equations. The program 2HDMC [4] also has this conversion between different basis choices built-in.

Likewise, the parameter Z_7 is not particularly intuitive, so one could advocate taking m_{12}^2 as the input parameter and computing Z_7 using eq. (3). However, m_{12}^2 is not a physical squared-mass, so there is no particular advantage for adopting this strategy. Indeed, a poor choice yields a value of Z_7 that violates unitarity constraints. Note that the $\mathcal{CP}$-conserving, softly-broken $\mathbb{Z}_2$-invariant 2HDM always requires one extra parameter beyond the four physical Higgs masses, α and β. We find that there is an advantage to choosing this parameter to be dimensionless for the reasons noted above. Another possible choice, often found in the literature, is λ_5 (in the generic basis), which is related to our parameters as

$$\lambda_5 = Z_5 + \tfrac{1}{2}(Z_6 - Z_7)\tan 2\beta\,. \tag{6}$$

One can therefore always trade in λ_5 for Z_7 and vice versa.

2 Constraints

For all numerical evaluations we use the code `2HDMC` [4] (v. 1.7.0), where the hybrid basis has been implemented. Constraints on the quartic couplings from (absolute) vacuum stability and S-matrix unitarity are evaluated at the input scale. For the case with $\mathbb{Z}_2$ symmetry (as is implicit already in the definition of the hybrid basis), the condition that the Higgs potential is positive definite is equivalent to the well-known relations

$$\lambda_1 > 0, \qquad \lambda_2 > 0, \qquad \lambda_3 > -\sqrt{\lambda_1\lambda_2},\,, \qquad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}. \tag{7}$$

For the unitarity constraints, we impose an upper limit which corresponds to saturation of the unitarity bound by the tree-level contribution. This is equivalent to the constraint $|\Lambda| < 16\,\pi$ on individual S-matrix elements in the notation of Ref. [5].

To determine our scenarios, constraints from direct Higgs searches at LEP, the Tevatron, and the LHC are evaluated using `HiggsBounds` [6] (v. 4.2.0), which selects for each parameter point the most sensitive exclusion limit (at 95% C.L.). The compatibility of the 2HDM with the observed 125 GeV

Higgs signal is calculated in terms of a χ^2 value taking into account the full LHC run-I data. This is done using `HiggsSignals` [7] (v. 1.3.0). To determine the viable parameter space regions in a benchmark scenario with two free parameters, we demand compatibility with the best-fit point, which usually is in very good agreement with the SM, within $2\,\sigma$ ($\Delta\chi^2 = \chi^2 - \chi^2_{\rm min} < 6.18$). The best-fit (minimal χ^2 value) is reevaluated for each benchmark scenario.

One additional constraint to keep in mind when designing viable benchmark scenarios are the electroweak precision tests, where in particular the oblique T parameter can receive sizeable contributions from large mass splittings. It should therefore be ensured either that $m_{H^\pm}^2 - m_A^2 \lesssim \mathcal{O}(v^2)$ or $m_{H^\pm}^2 - m_H^2 \lesssim \mathcal{O}(v^2)$ ($c_{\beta-\alpha} \ll 1$) to maintain approximate custodial symmetry and $T \simeq 0$. Finally, the general 2HDM (without supersymmetry) can also be constrained by various low-energy (flavour physics) processes (see, for example, Ref. [8]). Since our main objective is to define scenarios capturing interesting LHC phenomenology, we will not be concerned with the details of these constraints, nor will they be explicitly applied in our numerical results. It should however be noted that there exist generic lower bound on the charged Higgs boson mass in the Type-II 2HDM, $m_{H^\pm} \gtrsim 350$ GeV, from measurements of the BR($B \to X_s\gamma$).

Branching ratios and LHC cross sections for Higgs production for the proposed scenarios can most easily be evaluated using `2HDMC` and SusHi [9], in accordance with the recommendations of [10]. We further recommend that numerical values are also calculated with `HIGLU` [11] and `HDECAY` [12], since this provides indepedent verification of the results and a first estimate of the theoretical uncertainties in the treatment of (missing) higher-order corrections.

3 Benchmark scenarios

Scenario A (non-aligment)

This scenario has the "normal" interpretation of the 125 GeV signal as the lightest $\mathcal{CP}$-even Higgs boson, h, with SM-like properties. On the other hand, to allow for some interesting phenomenology of the heavier $\mathcal{CP}$-even state, H, we define the scenario with departure from alignment ($c_{\beta-\alpha} \neq 0$) as allowed by the present constraints. The scenario focuses on searches for the heavier $\mathcal{CP}$-even state, H, in SM final states plus the $H \to hh$ decay. The remaining two Higgs bosons, A and $H^\pm$ (which are kept mass-degenerate), are decoupled to a sufficient degree to create a small hierarchy $m_h = 125$ GeV $< m_H < m_A = m_{H^\pm}$. Input parameters are given in the hybrid basis.

Scenario A (non-alignment)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
A1.1	125	150 . . . 600	0.1	−2	−2	0	1 . . . 50	I
A1.2	125	150 . . . 600	$0.1 \times \left(\frac{150\text{ GeV}}{m_H}\right)^2$	−2	−2	0	1 . . . 50	I
A2.1	125	150 . . . 600	0.01	−2	−2	0	1 . . . 50	II
A2.2	125	150 . . . 600	$0.01 \times \left(\frac{150\text{ GeV}}{m_H}\right)^2$	−2	−2	0	1 . . . 50	II

In scenarios A1.1 and A2.1, where $c_{\beta-\alpha}$ fixed to a non-zero value independently of m_H, the range for $\tan\beta$ that is allowed by unitarity and stability constraints depends on the value of m_H. For higher H masses, the allowed range of $\tan\beta$ becomes more restrictive.

Scenario B (low-m_H)

Scenario B corresponds to a "flipped" 2HDM benchmark scenario. In this scenario both h and H are light, but it is the heavier of the two which has $m_H = 125$ GeV and is SM-like. Since $m_h < m_H$, the lighter Higgs must have strongly suppressed couplings to vector bosons to be compatible with direct search limits which forces $s_{\beta-\alpha} \to 0$. Input parameters are given in the hybrid basis.

Scenario B (low-m_H)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
B1.1	$65\ldots120$	125	1.0	-5	-5	0	1.5	I
B1.2	$80\ldots120$	125	0.9	-5	-5	0	1.5	I
B2	$65\ldots120$	125	1.0	-5	-5	0	1.5	II

Scenario C ($\mathcal{CP}$-overlap)

In this work we have restricted ourselves to benchmarks for a 2HDM Higgs sector with $\mathcal{CP}$-conservation. Nevertheless, we consider one scenario where overlapping $\mathcal{CP}$-odd and $\mathcal{CP}$-even Higgs bosons simultaneously have mass close to 125 GeV [13]. Since the $\mathcal{CP}$-odd Higgs boson does not couple to vector bosons at tree level, there are surprisingly few channels where it is possible to distinguish this scenario from the case with a single light Higgs, h. The most important channel where the $\mathcal{CP}$-odd contribution to the total rate could reach $\mathcal{O}(1)$ is through gluon ($b\bar{b}$) fusion, followed by the decay $h/A \to \tau^+\tau^-$. Input parameters are given in the physical basis. Note that the choice of $\lambda_5 = 0$ in this scenario is equivalent to $m_{12}^2 = \frac{1}{2}m_A^2 \sin 2\beta$.

Scenario C ($\mathcal{CP}$-overlap)								
	m_h	m_H	m_A	$m_{H^\pm}$	$c_{\beta-\alpha}$	λ_5	$\tan\beta$	Type
C1	125	300	125	300	0	0	$1\ldots10$	I
C2	125	300	125	300	0	0	$1\ldots10$	II

Scenario D (short cascade)

This scenario is constructed with a SM-like h by fixing $c_{\beta-\alpha}$ to be zero. The mass hierarchy can be modified allow for either one (or both) of the decay modes $H \to AZ$ or $H \to H^\pm W^\mp$ to be open. These decays can be dominant in the mass window 250 GeV $< m_H <$ 350 GeV (below $t\bar{t}$ threshold). Other decay modes that can be potentially of simultaneous interest is $H \to hh$ and $H \to AA$ (when A is very light). Realizations of Scenario D for all the interesting cases are given below. Input parameters are given in the hybrid basis.

Scenario D (short cascade)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
D1.1	125	$250\ldots500$	0	-1	1	-1	2	I
D1.2	125	$250\ldots500$	0	2	0	-1	2	I
D1.3	125	$250\ldots500$	0	1	1	-1	2	I
D2.1	125	$250\ldots500$	0	-1	1	-1	2	II
D2.2	125	$250\ldots500$	0	2	0	-1	2	II
D2.3	125	$250\ldots500$	0	1	1	-1	2	II

Scenario E (long cascade)

In this scenario we allow for long, two-step, cascade decays by choosing hierarchical masses among all three of the heavy Higgs bosons H, A and $H^\pm$. Possible decay chains are then $H^\pm \to AW^\pm \to HZW^\pm$ with the competing direct decay $H^\pm \to HW^\pm$, or $A \to H^\pm W^\mp \to W^\pm W^\mp H$ with the alternative $A \to ZH$, depending on the mass ordering of the heavy Higgs states. The input parameters are given in the hybrid basis.

Scenario E (long cascade)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
E1.1	125	$200\dots300$	0	-6	-2	0	2	I
E1.2	125	$200\dots300$	0	1	-3	0	2	I
E2.1	125	$200\dots300$	0	-6	-2	0	2	II
E2.2	125	$200\dots300$	0	1	-3	0	2	II

Scenario F (flipped Yukawa)

The flipped Yukawa scenario is characterized by SM-like couplings for the light Higgs, h, except for the couplings to down-type fermions which has a change of sign relative to the SM. This scenario is realized with Type-II Yukawa couplings for values of $(c_{\beta-\alpha}, t_\beta)$ solving the equation [14]

$$\frac{g_{hdd}}{g_{hdd}^{\mathrm{SM}}} = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha} = -1. \qquad (8)$$

For $\tan\beta \geq 1$, the solution to eq. (8) is $c_{\beta-\alpha} = \sin 2\beta$ (and $s_{\beta-\alpha} = -\cos 2\beta$ since we work in a convention where $s_{\beta-\alpha}$ is non-negative). Input parameters are given in the hybrid basis.

Scenario F (flipped Yukawa)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
F2	125	$150\dots600$	$\sin 2\beta$	-2	-2	0	$5\dots50$	II

Scenario G (MSSM-like)

Input parameters are given in the generic basis. The parameters g and g' denote the electroweak gauge couplings. The value of δ is determined by the requirement $m_h = 125$ GeV, subject to the constraint $\lambda_2 < 4\pi$, and the value of $m_{12}^2 = \frac{1}{2}m_A^2 \sin 2\beta$ is fixed by the chosen value of m_A and $\tan\beta$. The actual input parameters of this scenario can therefore be considered to be m_h, m_A and $\tan\beta$.

Scenario G (MSSM-like)								
	λ_1	λ_2	λ_3	λ_4	λ_5	m_A (GeV)	$\tan\beta$	Type
G2	$(g^2+g'^2)/4$	$(g^2+g'^2)/4+\delta$	$(g^2-g'^2)/4$	$-g^2/4$	0	$90\dots1000$	$1\dots60$	II

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