2HDM Benchmarks for Electroweak Cosmology (EWCosmo2HDM)

The introduction of a second Higgs doublet can spectacularly alter the cosmology of Electroweak (EW) theory by leading to a *strongly first order EW phase transition*, a pre-requisite for EW baryogenesis[1]. Demanding this feature points to a distinctive realisation of the 2HDM characterised by a unique 'smoking gun' signature.

The salient features of our proposed scenarios are a large mass splitting $m_{A_0} - m_{H_0} \sim v$, together with a fairly light H_0 ($m_{H_0} \lesssim 250$ GeV), which leads to a large $\mathrm{Br}(A_0 \to H_0 Z)$ as the distinctive signature. Our scenarios also feature a relatively small value of t_β, namely $1 \lesssim t_\beta \lesssim 5$, as required by successful EW baryogenesis [2]. We hereby propose four such benchmarks for the CP conserving 2HDM with natural flavour conservation. A preliminary collider analysis of two of these benchmarks (A1 & B1) has been performed in Ref. [1] finiding promising prospects for discovery/exclusion in the next run of the LHC[2].

The scalar potential we consider reads

$$V_{\rm tree}(\Phi_1, \Phi_2) = \mu_1^2 \left|\Phi_1\right|^2 + \mu_2^2 \left|\Phi_2\right|^2 - \frac{\mu^2}{2} \left[\Phi_1^\dagger \Phi_2 + \text{h.c.}\right] + \frac{\lambda_1}{2} \left|\Phi_1\right|^4 + \frac{\lambda_2}{2} \left|\Phi_2\right|^4 + \lambda_3 \left|\Phi_1\right|^2 \left|\Phi_2\right|^2 + \lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right]. \quad (1)$$

Potential (1) has 8 independent parameters, which we may rewrite in terms of $v = 246$ GeV, $m_h = 125$ GeV, $s_{\beta-\alpha}$, t_β, m_{H_0}, m_{A_0}, $m_{H^\pm}$, and μ (we follow the α and β conventions of Ref. [3]). We consider four different benchmark categories A1, A2, B1 and B2, with parameter values and possible search channels summarised in table 1, discussing them in more detail below.

	m_{H_0}	m_{A_0}	$m_{H^\pm}$	$s_{\beta-\alpha}$	t_β	μ	2HDM Type	Distinctive signature
A1	180	400	400	1	2	100	I, II	$A_0 \to H_0 Z \, (H_0 \to \bar{b}b)$
A2	180	400	180	1	3	50	I	$A_0 \to H_0 Z \, (H_0 \to \bar{b}b)$ $A_0 \to H^\pm W^\mp$
B1	180	400	400	0.95	2	100	I	$A_0 \to H_0 Z \, (H_0 \to WW)$
B2	160	430	160	0.95	3	100	I	$A_0 \to H_0 Z \, (H_0 \to WW)$ $A_0 \to H^\pm W^\mp$

Table 1: EWCosmo2HDM Benchmark Scenarios (masses in GeV).

[1]Our benchmarks are for CP conserving 2HDM. We find that the presence of a small CP phase in the scalar sector (which may ultimately be required to allow for EW baryogenesis) does not have an appreciable impact on the nature of the EW phase transition, nor on the LHC features of our presented benchmarks.

[2]Note the use of a different convention for α and β compared to this proposal.

The strength of the EW phase transition[3] for the benchmarks above is, in units of the required strength for successful baryogenesis: $2.2657, 1.0235, 1.8525, 1.1210$ respectively for $A1$, $A2$, $B1$ and $B2$.
All benchmark points pass the following constraints:

- EW precision observables;
- $\text{Br}(\bar{B} \to X_s \gamma)$ and $B^0 - \overline{B}^0$ mixing, which are the only relevant flavor constraints for low t_β [4];
- Unitarity [5] and perturbativity (quartics $< 4\pi$);
- Stability of potential at both tree [6] and loop level (for the latter, we check that the EW minimum is the global minimum up to a scale $\Lambda \sim 10$ TeV);
- Collider constraints using HiggsBounds [7] and HiggsSignals [8];
- Strongly first order electroweak phase transition.

Categories A and B differ from each other in how close they are to the *alignment limit* $s_{\beta-\alpha} = 1$, and each is subdivided twice according to the pairing of the charged scalar mass $m_{H^\pm}$, which is required to be close to either m_{A_0} or m_{H_0} to satisfy the experimental bounds on the T-parameter.

- A1: $m_{H^\pm} \simeq m_{A_0}$, $s_{\beta-\alpha} \simeq 1$. Being very close to SM alignment, this scenario satisfies the constraints from measured Higgs signal strengths and from heavy Higgs searches both for 2HDM *Type-I* and *Type-II* (and also *Lepton-Specific* and *Flipped*). Also, since $m_{H^\pm} \simeq m_{A_0} \gtrsim 400$ GeV, bounds from Flavour physics on $m_{H^\pm}$ are also respected for *Type-I* and *Type-II*.
- A2: $m_{H^\pm} \simeq m_{H_0}$, $s_{\beta-\alpha} \simeq 1$. As A1, except for the fact that now $m_{H^\pm} \simeq m_{H_0} \lesssim 250$ GeV, so the bounds from Flavour physics on $m_{H^\pm}$ are respected for *Type-I* but not for *Type-II*. Moreover, the decay $A_0 \to H^\pm W^\mp$ is allowed in addition to $A_0 \to H_0 Z$.
- B1: $m_{H^\pm} \simeq m_{A_0}$, $c_{\beta-\alpha} > 0.1$. Being fairly away from SM alignment, this scenario satisfies the constraints from measured Higgs signal strengths only for *Type-I*. Moreover, for bounds from heavy Higgs searches to be satisfied (due to direct production of H_0 in gluon fusion being suppressed), $c_{\beta-\alpha} > 0$ is needed. We also stress that bounds from $A_0 \to Zh$ away from SM alignment are much weaker in this scenario (and place essentially no constraint), since the dominant Branching Fraction of A_0 is into $H_0 Z$.
- B2: $m_{H^\pm} \simeq m_{H_0}$, $c_{\beta-\alpha} > 0.1$. As B1, but now the decay $A_0 \to H^\pm W^\mp$ is also possible.

For more details on the computation of the phase transition, we refer the reader to Ref. [9]. We note that this collider signature has also been discussed and analysed in Ref. [10].

[3] This is characterised by the ratio v_c/T_c, where v_c is the Higgs vacuum expectation value at the critical temperature, T_c.

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