2HDM—Report on recent activities

Howard E. Haber
Workshop of LHCHXSWG
13 June 2014

Outline

1. A CP-conserving 2HDM scalar potential and Yukawa interactions with no tree-level Higgs-mediated FCNCs: theoretical considerations
2. A hybrid strategy for specifying the model input parameters
3. Scenarios for 2HDM benchmarks
4. A couple of preliminary scans

reference: Howard E. Haber and Oscar Stål, work in progress.

The general 2HDM

The most general two-Higgs doublet model (2HDM) consists of two scalar doublet, hypercharge-one fields, Φ_1 and Φ_2, where $\langle\Phi_a^0\rangle = v_a/\sqrt{2}$ (for $a = 1,2$) are (possibly complex) vacuum expectation values (vevs) subject to $v^2 \equiv |v_1|^2 + |v_2|^2 = (246~\mathrm{GeV})^2$. By assumption, the minimum of the scalar potential conserves electric charge.

Employing the most general renormalizable scalar potential and Higgs-fermion Yukawa couplings generically yields:

- CP-violating Higgs interactions;
- neutral Higgs mass eigenstates that are not eigenstates of CP;
- Flavor-changing neutral currents (FCNCs) mediated at tree-level by neutral Higgs exchange.

The latter is not compatible with weak interaction experimental constraints.

A CP-conserving 2HDM with no tree-level Higgs-mediated FCNCs

By imposing a suitably chosen $\mathbb{Z}_2$ symmetry (which may be softly-broken) on the Higgs Lagrangian, one finds that the resulting 2HDM naturally has no tree-level Higgs-mediated FCNCs. We further simplify by assuming that the scalar potential is CP-conserving. The corresponding scalar potential is:

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \tfrac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \tfrac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \left[\tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right] ,$$

where m_{12}^2 softly breaks the $\mathbb{Z}_2$ symmetry. In particular, we do not allow a hard breaking of the $\mathbb{Z}_2$ symmetry, which implies that the term of the form $(\Phi_1^\dagger \Phi_2)(\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2) + \text{h.c.}$ is absent.

<u>Note</u>: we assume that the parameters m_{12}^2 and λ_5 are real and take on a range of values that is consistent with a CP-conserving vacuum, in which case the vevs v_1 and v_2 can be chosen real and non-negative.

The Higgs–fermion interactions

When re-expressed in terms of the quark and lepton mass-eigenstate fields, $U=(u,c,t)$, $D=(d,s,b)$, $N=(\nu_e,\nu_\mu,\nu_\tau)$, and $E=(e,\mu,\tau)$,

$$-\mathcal{L}_{\rm Y}=\overline{U}_L\Phi_a^{0\,*}h_a^U U_R-\overline{D}_L K^\dagger\Phi_a^- h_a^U U_R+\overline{U}_L K\Phi_a^+ h_a^{D\,\dagger}D_R+\overline{D}_L\Phi_a^0 h_a^{D\,\dagger}D_R$$
$$+\overline{N}_L\Phi_a^+ h_a^{E\,\dagger}E_R+\overline{E}_L\Phi_a^0 h_a^{E\,\dagger}E_R+{\rm h.c.}\,,\qquad \text{(summed over } a=1,2)$$

where K is the CKM quark mixing matrix, $h^{U,D,L}$ are 3×3 Yukawa coupling matrices. Applying the $\mathbb{Z}_2$ symmetry leads to four distinct model types:

1. Type-I Yukawa couplings: $h_1^U=h_1^D=h_1^L=0$,
2. Type-II Yukawa couplings: $h_1^U=h_2^D=h_2^L=0$,
3. Type-X Yukawa couplings: $h_1^U=h_1^D=h_2^L=0$,
4. Type-Y Yukawa couplings: $h_1^U=h_2^D=h_1^L=0$.

The Higgs basis of the CP-conserving softly-broken $\mathbb{Z}_2$ symmetric 2HDM

It is convenient to define new Higgs doublet fields in the *Higgs basis*:

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1\Phi_1 + v_2\Phi_2}{v}\,, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v}\,.$$

It follows that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$. The scalar potential is:

$$\begin{aligned}\mathcal{V} = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] + \tfrac{1}{2}Z_1(H_1^\dagger H_1)^2 \\ & + \tfrac{1}{2}Z_2(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{\tfrac{1}{2}Z_5(H_1^\dagger H_2)^2 + \left[Z_6(H_1^\dagger H_1) + Z_7(H_2^\dagger H_2)\right]H_1^\dagger H_2 + \text{h.c.}\right\}.\end{aligned}$$

After minimizing the scalar potential, $Y_1 = -\frac{1}{2}Z_1 v^2$ and $Y_3 = -\frac{1}{2}Z_6 v^2$. Under the assumption of a CP-conserving scalar potential and vacuum, all scalar potential parameters can be taken real. The real Higgs basis is uniquely defined up to $H_2 \to -H_2$. Thus, we introduce the *pseudo-invariants*,

$$\varepsilon_6 \equiv \text{sgn}\ Z_6\,, \qquad \varepsilon_7 \equiv \text{sgn}\ Z_7\,,$$

which change sign under the real Higgs basis transformation $H_2 \to -H_2$.

The charged Higgs boson is the charged component of the Higgs-basis doublet H_2, and its mass is given by $m_{H^\pm}^2 = Y_2 + \frac{1}{2} Z_3 v^2$. The three physical neutral Higgs boson mass-eigenstates are determined by diagonalizing a 3×3 real symmetric squared-mass matrix that is defined in the Higgs basis

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 & 0 \\ Z_6 v^2 & Y_2 + \frac{1}{2}(Z_3 + Z_4 + Z_5) v^2 & 0 \\ 0 & 0 & Y_2 + \frac{1}{2}(Z_3 + Z_4 - Z_5) v^2 \end{pmatrix} .$$

We immediately identify the CP-odd Higgs boson $A = \sqrt{2}\, \varepsilon_6 \, \mathrm{Im}\; H_2^0$ with squared mass, $m_A^2 = Y_2 + \frac{1}{2}(Z_3 + Z_4 - Z_5) v^2$.

To diagonalize the upper 2×2 matrix block, we define the CP-even mass eigenstates, h and H (with $m_h \leq m_H$) by

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_{12} & -s_{12} \\ s_{12} & c_{12} \end{pmatrix} \begin{pmatrix} \sqrt{2}\; \mathrm{Re}\; H_1^0 - v \\ \sqrt{2}\, \varepsilon_6 \, \mathrm{Re}\; H_2^0 \end{pmatrix} ,$$

where $c_{12} \equiv \cos\theta_{12}$ and $s_{12} \equiv \sin\theta_{12}$. By convention, $-\frac{1}{2}\pi \leq \theta_{12} \leq \frac{1}{2}\pi$.

We have yet to impose the $\mathbb{Z}_2$ symmetry. In the Φ_1–Φ_2 basis, we have $\lambda_6 = \lambda_7 = 0$, which yields:

$$(Z_1 - Z_2)\big[Z_1 Z_7 + Z_2 Z_6 - Z_{345} Z_{67}\big] + 2Z_{67}^2 (Z_6 - Z_7) = 0\,,$$

where $Z_{345} \equiv Z_3 + Z_4 + Z_5$ and $Z_{67} \equiv Z_6 + Z_7$. Moreover, the parameter $\tan\beta \equiv \langle\Phi_2^0\rangle/\langle\Phi_1^0\rangle$ is determined,

$$\tan 2\beta = \frac{2\tan\beta}{1-\tan^2\beta} = \frac{2Z_{67}}{Z_2 - Z_1}\,.$$

That is, $\tan\beta$ is a pseudo-invariant quantity. It is conventional to define $\tan\beta$ to be non-negative, in which case the two-fold freedom in defining the real Higgs basis is removed. Thus, we henceforth assume that $0 \leq \beta \leq \frac{1}{2}\pi$.

Note: If $Z_6 = -Z_7 \neq 0$ then $Z_1 = Z_2$, in which case $\tan 2\beta$ is the solution to the quadratic equation, $(Z_1 - Z_{345})\tan 2\beta + 2Z_6(1 - \tan^2 2\beta) = 0$. The case of $Z_6 = Z_7 = 0$ yields the inert 2HDM, which can be treated separately.

In the Φ_1–Φ_2 basis, the CP-even Higgs mixing angle is denoted by α, and is given by

$$\alpha = \beta - \theta_{12} - \tfrac{1}{2}\pi \,.$$

We write $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$ and $c_{\beta-\alpha} \equiv \cos(\beta-\alpha)$. In this notation,

$$\cos\theta_{12} = s_{\beta-\alpha}\,, \qquad\qquad \sin\theta_{12} = -\varepsilon_6\, c_{\beta-\alpha}\,,$$

which implies that $0 \leq \beta-\alpha \leq \pi$. Moreover, $c_{\beta-\alpha}$ is a pseudo-invariant quantity. An explicit computation yields

$$c^2_{\beta-\alpha} = \frac{Z_1 v^2 - m_h^2}{m_H^2 - m_h^2}\,,$$

$$s_{\beta-\alpha}c_{\beta-\alpha} = -\frac{Z_6 v^2}{m_H^2 - m_h^2},.$$

Since $0 \leq s_{\beta-\alpha} \leq 1$ by convention, it follows that $Z_6 c_{\beta-\alpha} \leq 0$.

Note: the decoupling limit ($m_H \gg m_h$) implies $|c_{\beta-\alpha}| \ll 1$, whereas the alignment limit ($|Z_6| \ll 1$) yields either $|c_{\beta-\alpha}| \ll 1$ or $s_{\beta-\alpha} \ll 1$.

A hybrid strategy for specifying the model input parameters

We choose as an input parameter set,

$$\{m_h, m_H, s_{\beta-\alpha}, \tan\beta, Z_4, Z_5, Z_7, \varepsilon_6 = \pm 1\}\,,$$

in a convention where $\tan\beta \geq 0$ and $0 \leq s_{\beta-\alpha} \leq 1$. Note that the sign of $c_{\beta-\alpha}$ is determined by the constraint $\varepsilon_6 c_{\beta-\alpha} \leq 0$.

Key features are as follows:

- Uses the Higgs data to fix one CP-even Higgs mass and constrain the range for $s_{\beta-\alpha}$ which determines the CP-even Higgs couplings to ZZ (or WW).
- Easy to implement theoretical constraints on parameters (e.g., unitarity limits for the Z_i).
- Easy to implement phenomenological constraints on parameters (e.g., restrictions in $[\tan\beta\,, m_{H^\pm}]$ parameter space due to B physics observables).

The masses of A and $H^\pm$ are determined,

$$m_A^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - Z_5 v^2\,, \qquad m_{H^\pm}^2 = m_A^2 - \tfrac{1}{2}(Z_4 - Z_5)v^2\,.$$

All other Higgs basis parameters are also determined:

$$\begin{aligned}
Z_1 &= \frac{s_{\beta-\alpha}^2 m_h^2 + c_{\beta-\alpha}^2 m_H^2}{v^2}\,,\\
Z_6 &= \frac{(m_h^2 - m_H^2)s_{\beta-\alpha}c_{\beta-\alpha}}{v^2}\,,\\
Z_2 &= \frac{s_{\beta-\alpha}^2 m_h^2 + c_{\beta-\alpha}^2 m_H^2}{v^2} + \frac{1-\tan^2\beta}{\tan\beta}\left(\frac{(m_h^2 - m_H^2)s_{\beta-\alpha}c_{\beta-\alpha}}{v^2} + Z_7\right)\\
Z_3 &= \frac{Z_1 Z_7 + Z_2 Z_6}{Z_6 + Z_7} + \frac{2(Z_6^2 - Z_7^2)}{Z_1 - Z_2} - Z_4 - Z_5\,.
\end{aligned}$$

The expression for Z_3 cannot be used if either $Z_{67} = 0$ and/or $Z_1 = Z_2$. These special cases can be separately treated.

Benchmark scenarios

A. h is SM-like; $m_A \sim m_{H^\pm} > 350$ GeV; search for H. We take $Z_4 = Z_5 = -2$ so that H is the second lightest Higgs boson. For simplicity, $Z_7 = 0$.

B. H is SM-like, h is weakly coupled to WW/ZZ; $m_A \sim m_{H^\pm} > 350$ GeV.

C. h SM-like; $m_h \simeq m_A$. Can be achieved by fine-tuning Z_5.

D. h is SM-like; decay channels $H \to AZ$ and/or $H \to H^\pm W^\mp$ are open.

E. h is SM-like; decay channels $H^\pm \to AW^\pm$ or $A \to H^\pm W^\mp$ are open.

F. h has SM-like couplings to WW/ZZ and up-type fermions. Coupling to down-type fermions is SM-like in magnitude but opposite in sign [cf. P.M. Ferreira et al.,Phys. Rev. D **89**, 115003 (2014)].

G. MSSM-like scenario for heavy Higgs bosons.

Remarks

- If h is SM-like, then we are either in the decoupling limit, $m_{H,A,H^\pm} \gg m_h$, or in the alignment limit where $|Z_6| \ll 1$. In both cases, $|c_{\beta-\alpha}| \ll 1$ and $s_{\beta-\alpha}$ is near 1. Note that the masses of H, A and $H^\pm$ need not be significantly larger than the mass of h in the alignment limit.

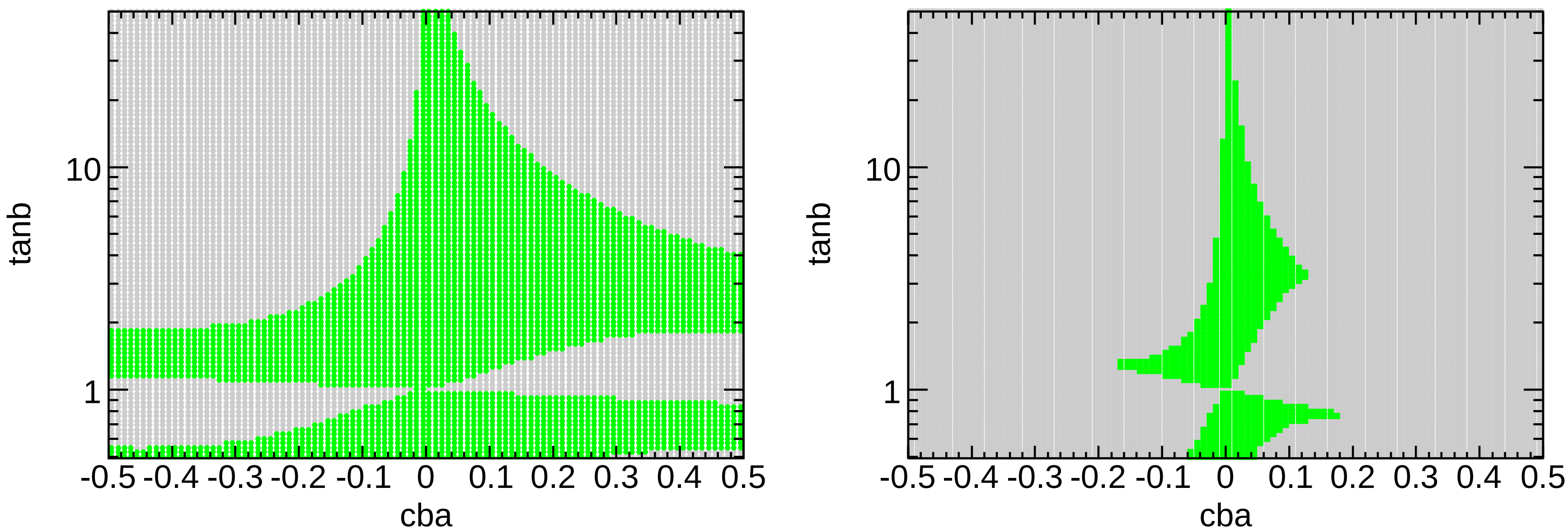
- If H is SM-like, then $s_{\beta-\alpha} \ll 1$ and $|c_{\beta-\alpha}|$ is near 1. This occurs in the alignment limit where $|Z_6| \ll 1$, but is not possible in the decoupling limit.

- Scenarios A–E are considered for both Type-I and Type-II Yukawa couplings. Scenarios F and G are only relevant for Type-II Yukawa couplings.

- All the scenarios are implemented through the program `2HDMC`, which allows for easy translation to other 2HDM parameter bases.

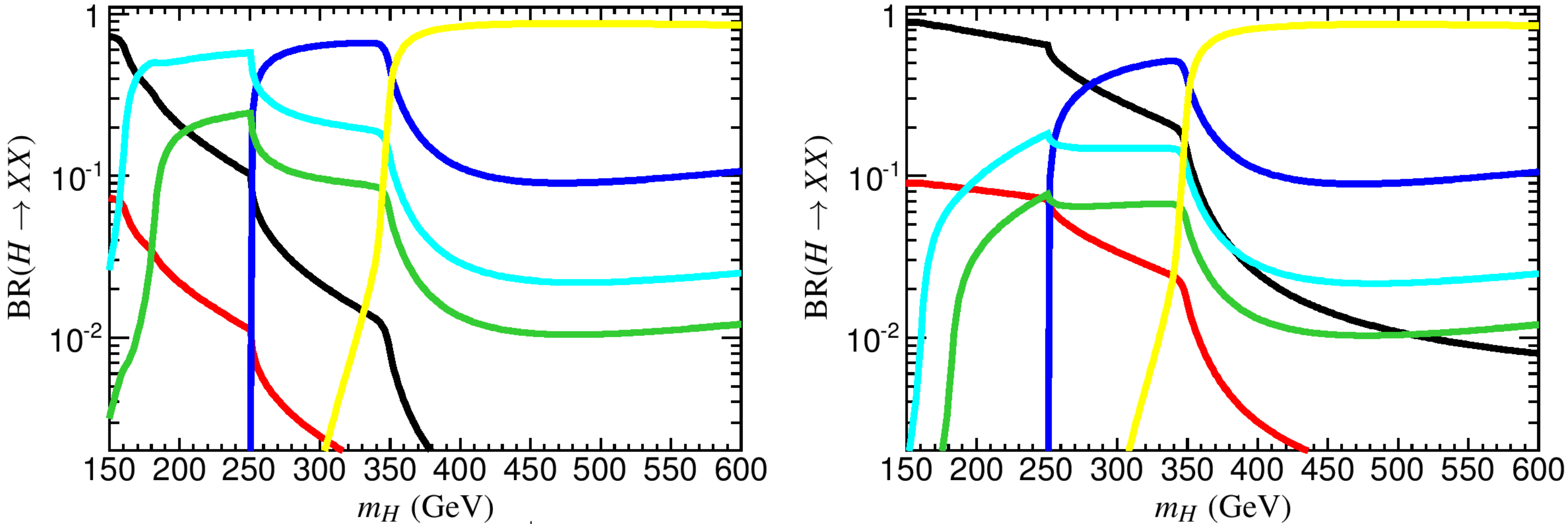
- Very preliminary scans have been carried out for Scenarios A and B. Stay tuned for further results in the near future.

Scenario A

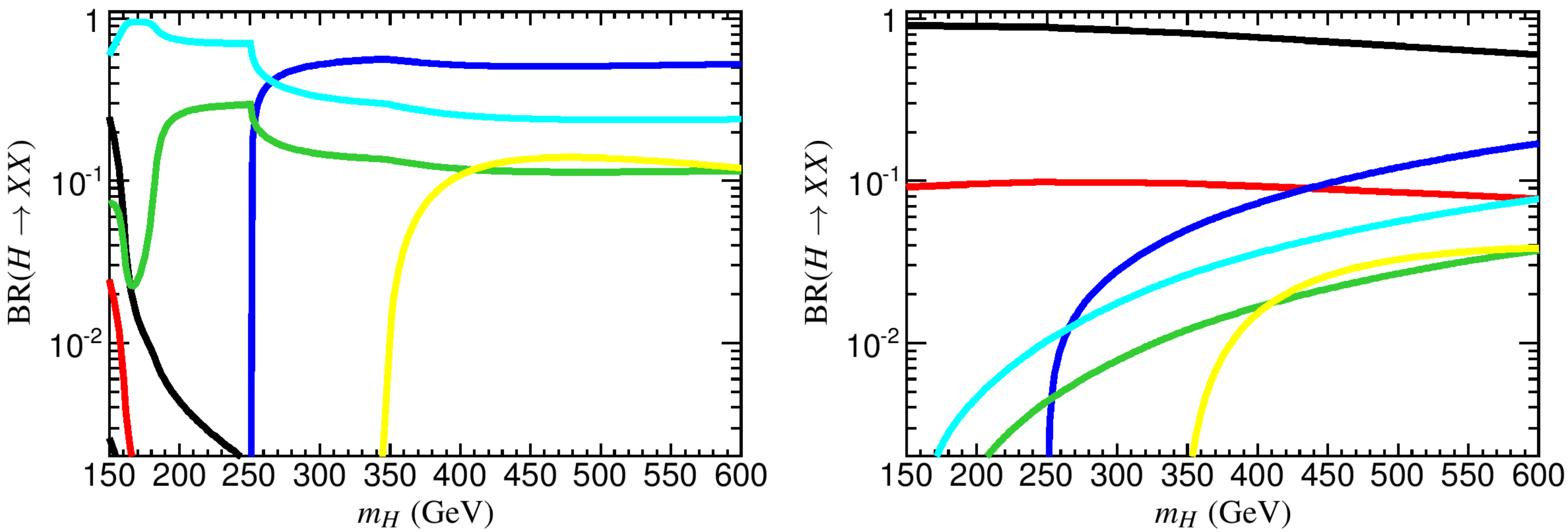


Parameter regions in Scenario A in the $c_{\beta-\alpha}$ vs. $\tan\beta$ plane respecting perturbativity, unitarity and stability constraints (green) for $m_H = 250$ GeV (left) and $m_H = 500$ GeV (right) with Type-II Yukawa couplings.

We fix our benchmark scenarios by taking $Z_4 = Z_5 = -2$, $Z_7 = 0$, and $c_{\beta-\alpha} = 0.0447$. Two cases of $\tan\beta = 2$ and 10 are considered for Type-I and Type-II Yukawa couplings. We scan over the range $150\ \mathrm{GeV} < m_H < 600$ GeV. The relevant H branching ratios are presented.



$H \to b\bar{b}$ (black), $H \to \tau\tau$ (red), $H \to W^+W^-$ (cyan), $H \to ZZ$ (green), $H \to hh$ (blue), $H \to t\bar{t}$ (yellow), for $\tan\beta = 2$.

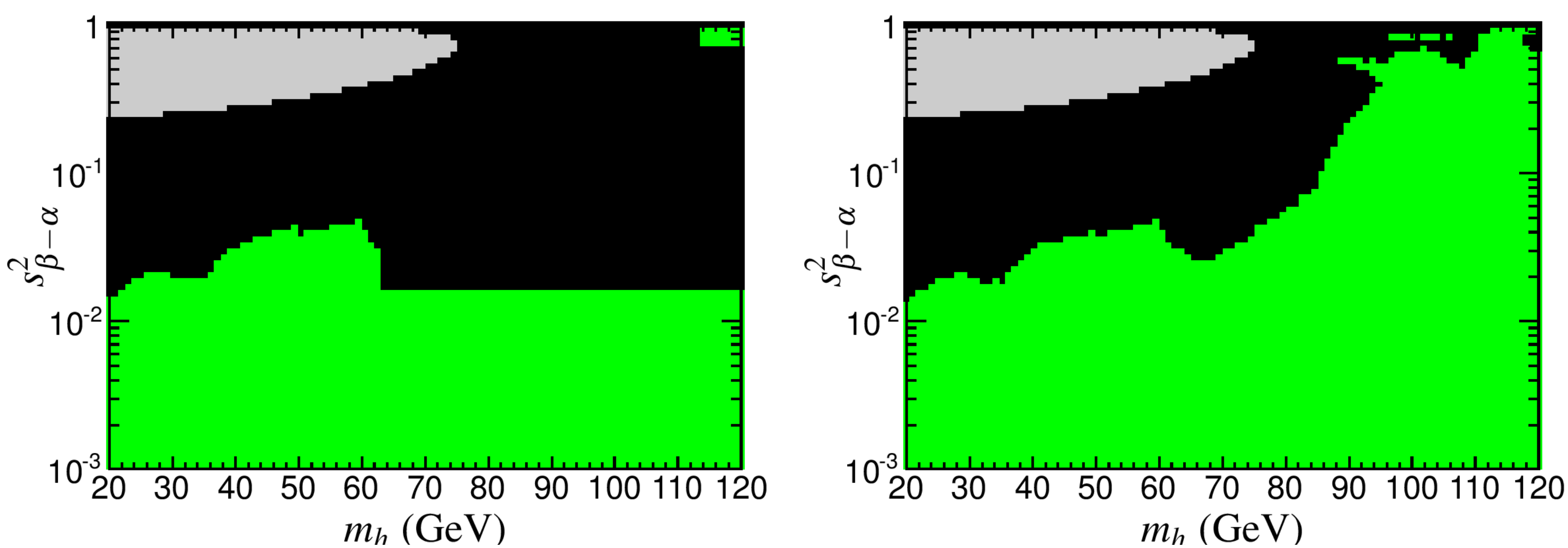


$H \to b\bar{b}$ (black), $H \to \tau\tau$ (red), $H \to W^+W^-$ (cyan), $H \to ZZ$ (green), $H \to hh$ (blue), $H \to t\bar{t}$ (yellow), for $\tan\beta = 10$.

Type-I Yukawa couplings (left); Type-II Yukawa couplings (right).

Scenario B: This is the "flipped" 2HDM benchmark scenario (h and H light) with $m_H \sim 126$ GeV (SM-like) and $m_h < m_H$, with strongly reduced couplings of h to WW/ZZ. The other two states, A and $H^{\pm}$, are decoupled to a sufficient degree not to affect the phenomenology (similar to scenario A). The Yukawa couplings in this scenario can be of either type I [left] or type II [right].

In the parameter space region $90 < m_h < 120$ GeV, LHC constraints (from $h \to bb, \tau\tau$) apply, which leads to an upper limit on $\tan\beta$. We choose $\tan\beta = 1.5$ in the figures below.



Allowed regions subject to stability, perturbativity and unitarity constraints (black) and LHC/LEP constraints via HiggsBounds (green).