LHC Benchmarks for the CP-conserving 2HDM

Howard E. Haber
2HDM benchmark discussion
CERN, 23 June 2015

Outline

1. The CP-conserving softly-broken $\mathbb{Z}_2$-symmetric 2HDM
2. The alignment limit
3. A hybrid strategy for specifying the model input parameters
4. 2HDM benchmarks scenarios

reference: Howard E. Haber and Oscar Stål, to appear soon on the arXiv.

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

- The scalar potential $\mathcal{V}(\Phi_1, \Phi_2)$ consists of real squared-mass parameters m_{ih}^2 and quartic coupling parameters λ_i, and the vacuum expectation values, $\langle \Phi_i^0 \rangle \equiv v_i$, are real. Define $\tan\beta \equiv v_2/v_1$.

- Due to the $\mathbb{Z}_2$ symmetry of the dimension-4 terms of the Higgs Lagrangian, a term in $\mathcal{V}$ of the form $\big(\Phi_1^\dagger \Phi_2\big)\big(\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2\big) + \text{h.c.}$ is absent.

- Extending the $\mathbb{Z}_2$ to the Higgs-fermion interactions can be done in one of four ways, leading to Type-I, II, X or Y Yukawa couplings. This eliminates tree-level Higgs-mediated FCNCs.

- Defining the Higgs basis such that $\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$.

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

- In the Higgs basis, the coefficients of the quartic terms of $\mathcal{V}$ are denoted by Z_i $(i = 1, 2, \ldots, 7)$. Two relations exist due to the $\mathbb{Z}_2$ symmetry.

The alignment limit

The two CP-even scalars are h and H with $m_h < m_H$ and corresponding mixing angle α. If h is SM-like (as suggested by the Higgs data), then

$$g_{hVV}/g_{h_{\rm SM}VV} = s_{\beta-\alpha} \simeq 1\,,$$

Indeed, for $c_{\beta-\alpha} = 0$, h is exactly aligned with $\sqrt{2}\,{\rm Re}\,H_1^0 - v$ and behaves exactly like the SM-like Higgs. Approximate alignment implies that $|c_{\beta-\alpha}| \ll 1$.

$$c_{\beta-\alpha} = -{\rm sgn}(Z_6)\sqrt{\frac{Z_1 v^2 - m_h^2}{m_H^2 - m_h^2}} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}}\,,$$

implies that $m_h^2 \simeq Z_1 v^2$ and approximate alignment is achieved if either $|Z_6| \ll 1$ and/or $m_H \gg m_h$. The limit $m_H \gg m_h$ corresponds to the decoupling limit. Alignment without decoupling is possible if $|Z_6| \ll 1$.

Note that $g_{HVV}/g_{h_{\rm SM}VV} = c_{\beta-\alpha}$, so it is possible to have H as the SM-like Higgs boson if $|s_{\beta-\alpha}| \ll 1$. In this case, further manipulation of the above equation yields $m_H^2 \simeq Z_1 v^2$ and once again, alignment without decoupling is possible if $|Z_6| \ll 1$. (In this case no decoupling limit exists.)

A hybrid strategy for specifying the model input parameters

We choose as an input parameter set,

$$\{m_h, m_H, c_{\beta-\alpha}, \tan\beta, Z_4, Z_5, Z_7\},$$

in a convention where $0 \leq \beta \leq \frac{1}{2}\pi$ and $0 \leq \beta - \alpha \leq \pi$.

Key features are as follows:

- Uses the Higgs data to fix one CP-even Higgs mass and constrain the range for $c_{\beta-\alpha}$ which is determined by the CP-even Higgs couplings to ZZ/WW.
- Easy to implement theoretical constraints on parameters (e.g., perturbativity limits for the Z_i); useful for 2HDM parameter scans.
- Easy to implement phenomenological constraints on parameters (e.g., restrictions in $[\tan\beta\,, m_{H^\pm}]$ parameter space due to B physics observables).
- All Higgs-basis parameters are determined from the above set, which fixes the 2HDM model precisely.

The masses of A and $H^\pm$ are determined by Z_4 and Z_5,

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

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

Keeping Z_4, $Z_5 \sim \mathcal{O}(1)$ ensures that unitarity, perturbativity and the S and T constraints are respected. We sometimes utilize three special cases in our scans:

$$\begin{aligned}
m_A = m_{H^\pm} \quad &\Longleftrightarrow \quad Z_4 = Z_5\,,\\
m_H = m_{H^\pm} \text{ and } c_{\beta-\alpha} = 0 \quad &\Longrightarrow \quad Z_4 = -Z_5\,,\\
m_H = m_A \text{ and } c_{\beta-\alpha} = 0 \quad &\Longrightarrow \quad Z_5 = 0\,.
\end{aligned}$$

Z_7 can be traded in for the $\mathbb{Z}_2$ symmetry-breaking soft squared-mass term m_{12}^2 or for the dimensionless coupling λ_5, via

$$\overline{m}^{\,2} \equiv \frac{m_{12}^2}{s_\beta c_\beta} = m_A^2 + \lambda_5 v^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 + \tfrac{1}{2}\tan 2\beta (Z_6 - Z_7) v^2\,,$$

where $Z_6 v^2 = (m_h^2 - m_H^2) s_{\beta-\alpha} c_{\beta-\alpha}$.

Benchmark scenarios

A. h is SM-like; $m_A \sim m_{H^\pm}$ large to avoid B–constraints. Take $Z_4 = Z_5 = -2$ so that H is the second lightest Higgs boson. Search for H. $Z_7 = 0$; $\tan\beta = 1 \ldots 50$.

B. H is SM-like, hVV ($V = W^\pm$ or Z) is weakly coupled. Search for h. $Z_7 = 0$; $\tan\beta \sim 1.5$; $m_A \sim m_{H^\pm}$ large.

C. h SM-like; $m_h \simeq m_A$; $m_A \sim m_{H^\pm}$ large. 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; "long cascade" decay channels $H^\pm \to AW^\pm \to HZW^\pm$ or $A \to H^\pm W^\mp \to HW^+W^-$ are open.

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

G. MSSM-like scenario for heavy Higgs bosons in a Type-II 2HDM.

Numerical Procedure

1. 2HDM constraints (e.g., vacuum stability, unitarity) implemented by the code `2HDMC` .

2. Numerical analysis of branching ratios and cross sections based on the codes `2HDMC` and `SusHi`.

3. Implementing constraints from direct Higgs searches are evaluated using `HiggsBounds`.

4. Implementing constraints due to the observation of a SM-like Higgs boson are evaluated using `HiggsSignals`.

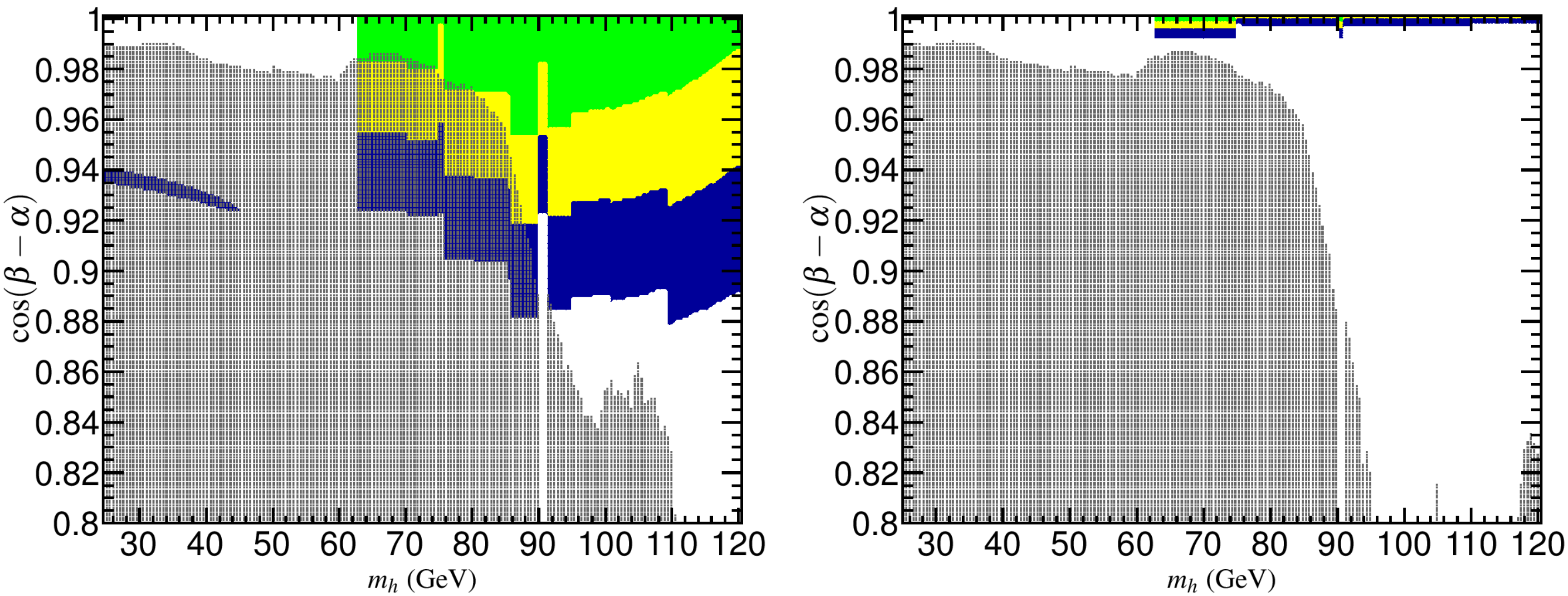
5. T-parameter constraints easily accommodated by taking $m^2_{H^\pm} - m^2_A \lesssim \mathcal{O}(v^2)$ or $m^2_{H^\pm} - m^2_H \lesssim \mathcal{O}(v^2)$.

6. Flavor constraints apply in a pure 2HDM. The latest result of M. Misiak et al., Phys. Rev. Lett. **114**, 221801 (2015), based on the observed $b \to s\gamma$ rate yields $m_{H^\pm} \gtrsim 480$ GeV at 95% CL in a Type-II 2HDM.

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	$150\dots600$	0.1	-2	-2	0	$1\dots50$	I
A1.2	125	$150\dots600$	$0.1 \times \left(\frac{150\text{ GeV}}{m_H}\right)^2$	-2	-2	0	$1\dots50$	I
A2.1	125	$150\dots600$	0.01	-2	-2	0	$1\dots50$	II
A2.2	125	$150\dots600$	$0.01 \times \left(\frac{150\text{ GeV}}{m_H}\right)^2$	-2	-2	0	$1\dots50$	II

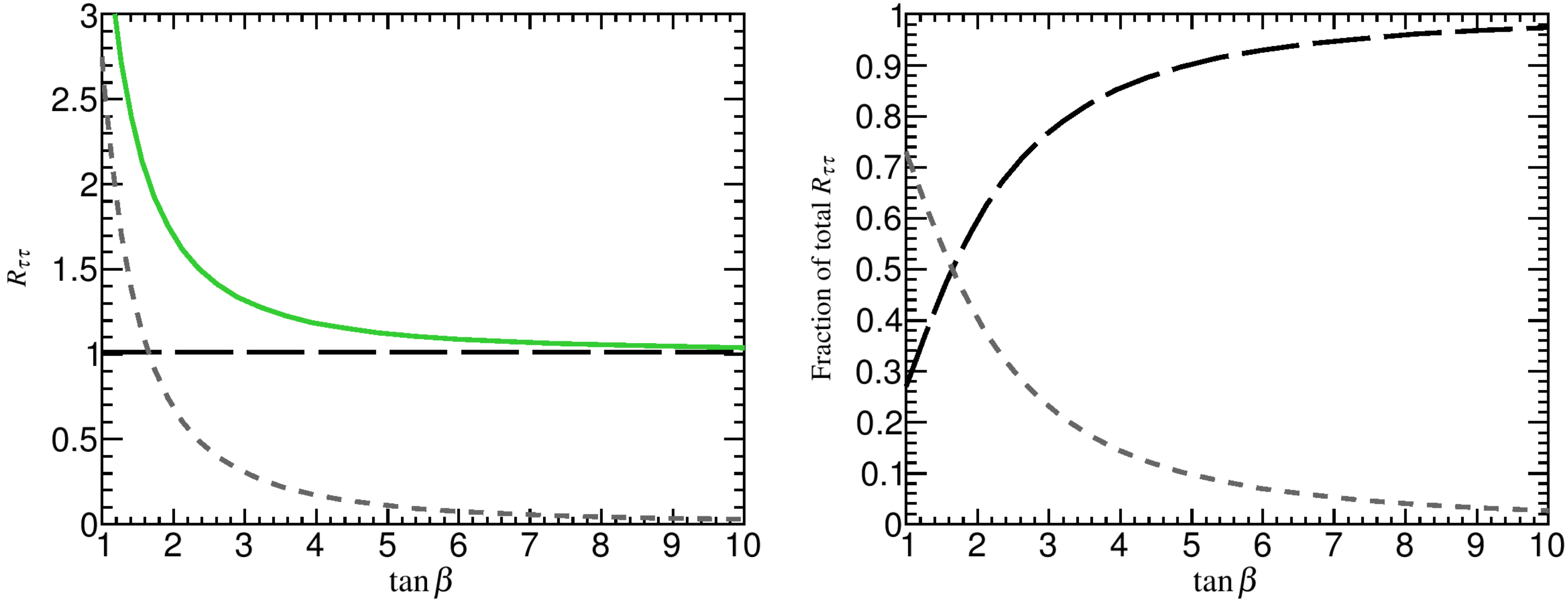
- All values of $\tan\beta$ allowed and $c_{\beta-\alpha} \lesssim 0.1$ in Type-I; $\tan\beta \lesssim 10$ favored and $c_{\beta-\alpha} \lesssim 0.01$ in Type-II.
- Cross sections are largest for low $\tan\beta$ (enhanced t-quark loop). Region of enhanced b quark loop in Type-II at large $\tan\beta$ disfavored by direct searches for H and A.
- For Type-I at $c_{\beta-\alpha} = 0.1$ and low $\tan\beta$, $H \to VV$ dominate for $m_H < 250$ GeV, $H \to hh$ dominates for $m_H = 250$—350 GeV, $H \to t\bar{t}$ dominates for $m_H > 350$ GeV.
- For Type-II at $c_{\beta-\alpha} = 0.01$, fermionic decays of H are most important. At low $\tan\beta$ $H \to hh$ can reach 10% BR for $m_H \sim 300$ GeV.
- Suggestion: choose $\tan\beta = 1.5$ and 10 as representative points and scan over m_H.

Scenario B (SM-like 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



Allowed parameter regions for h in Scenario B with Type-I Yukawa couplings (left) and Type-II couplings (right). The colors indicate statistical compatibility with the 125 GeV Higgs signal at $1\,\sigma$ (green), $2\,\sigma$ (yellow) and $3\,\sigma$ (blue). The gray region is excluded at 95% C.L. by constraints from direct searches at LEP and the LHC.

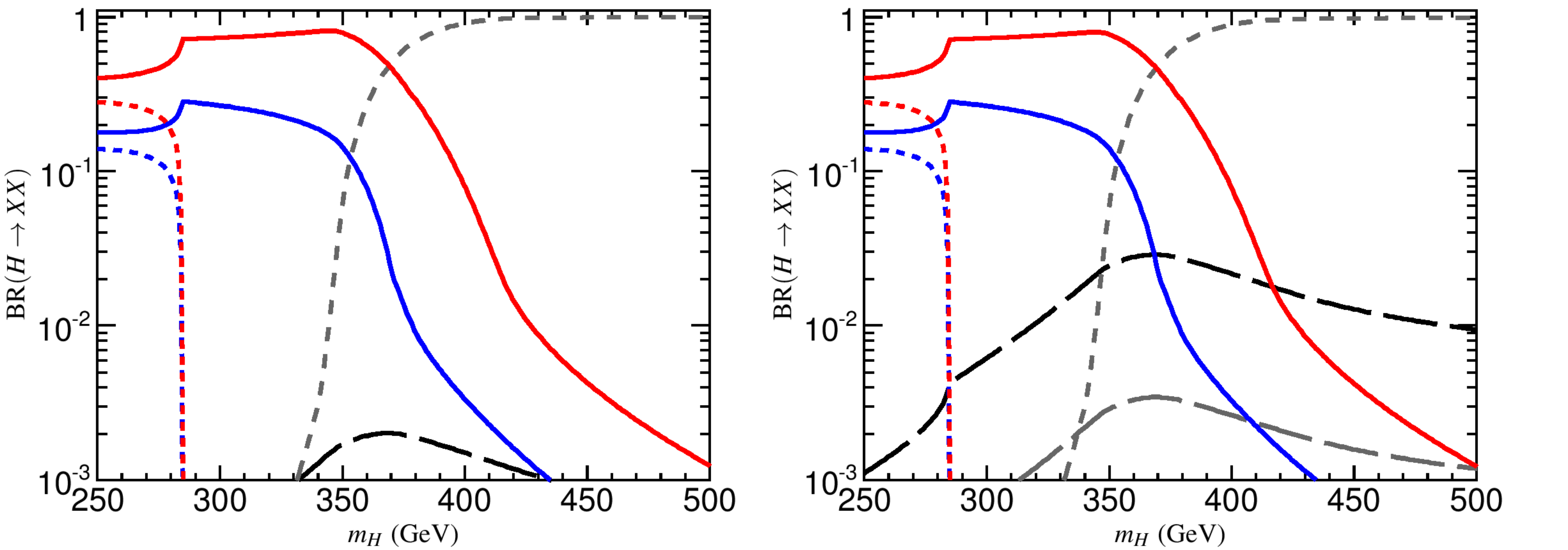
Scenario C (CP-overlap)								
	m_h	m_H	m_A	$m_{H^\pm}$	$c_{\beta-\alpha}$	λ_5	$\tan\beta$	Type
C1	125	300	125	300	0	0	$1\ldots10$	I
C2	125	300	125	300	0	0	$1\ldots10$	II



In Scenario C with Type-I Yukawa couplings , the total $\tau\tau$ rate (adding gg and $b\bar{b}$ production modes), relative to the SM, from h (long dashes), A (short dashes) and their sum (green, solid). Right: the respective fractions of the inclusive $\tau\tau$ rate resulting from h (long dashes) and A (short dashes).

Note: In Type-II models, the signal strength $R_{\tau\tau} > 1.5$ for all $\tan\beta$, since $\sigma(b\bar{b} \to A)$ is enhanced at large $\tan\beta$ and $\sigma(gg \to A)$ is enhanced at small $\tan\beta$.

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



Branching ratios of H in Scenario D with both m_A and $m_{H^\pm}$ low for $\tan\beta = 2$ with Type-I (left) and Type-II (right) Yukawa couplings. The colors show $H \to ZA$ (blue, solid), $H \to AA$ (blue, short dash), $H \to W^\pm H^\mp$ (red, solid), $H \to H^+H^-$ (red, short dash), $H \to t\bar{t}$ (gray, dash) and $H \to b\bar{b}$ (black, long dash) and $H \to \tau\tau$ (gray, long dash).

Scenario E (Long cascade)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
E(1,2).1	125	$200\ldots300$	0	-6	-2	0	2	I, II
E(1,2).2	125	$200\ldots300$	0	1	-3	0	2	I, II

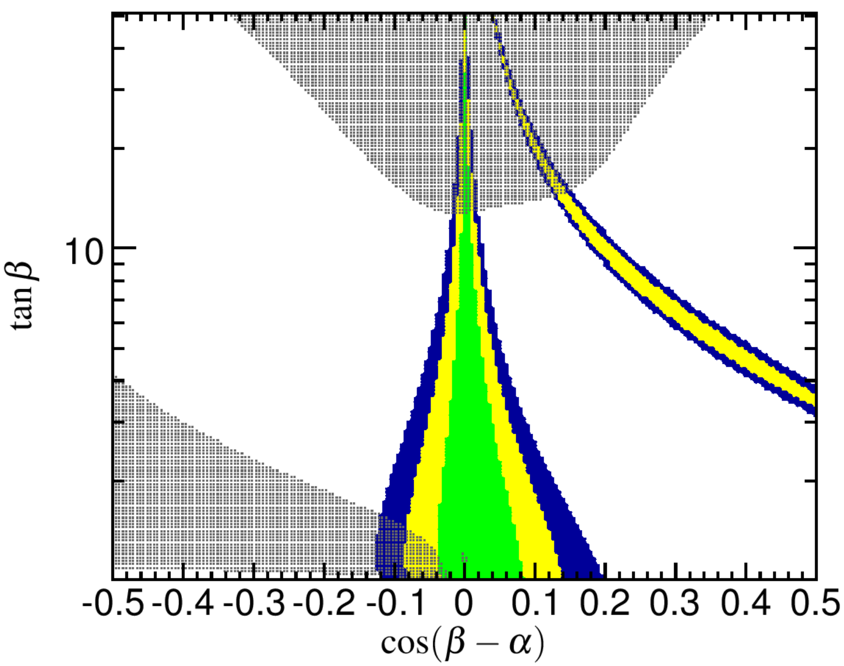
- Choose 2HDM parameters to allow two step decays involving all three non-SM Higgs bosons. Assume that H is the lightest.
- Competing decays: $H^\pm \to AW^\pm \to HZW^\pm$ and $H^\pm \to W^\pm H$.
- Competing decays: $A \to H^\pm W^\mu \to HW^+W^-$ and $A \to ZH$
- Branching ratios for two step decays are typically around 5%.

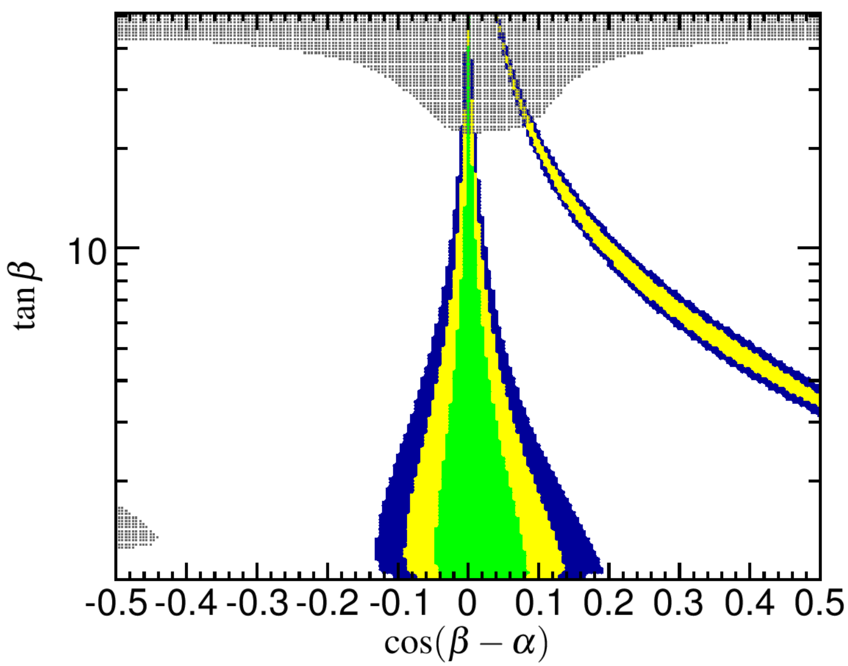
Scenario	Masses (GeV)			Branching ratios			
	m_H	m_A	$m_{H\pm}$	$H^\pm \to W^\pm A$	$H^\pm \to W^\pm\ H$	$A \to ZH$	$A^\pm \to W^\pm H^\mp$
E1	200	402	532	0.053	0.79	0.62	–
	300	460	577	0.041	0.74	0.39	–
E2	200	471	317	–	0.27	0.56	0.25
	300	521	388	–	0.026	0.50	0.20

Mass spectrum and branching ratios of interesting decay modes in Scenario E.

Scenario F (Flipped Yukawa)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
F2	125	$150\ldots600$	$\sin 2\beta$	-2	-2	0	$5\ldots50$	II

$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta = -1.$$

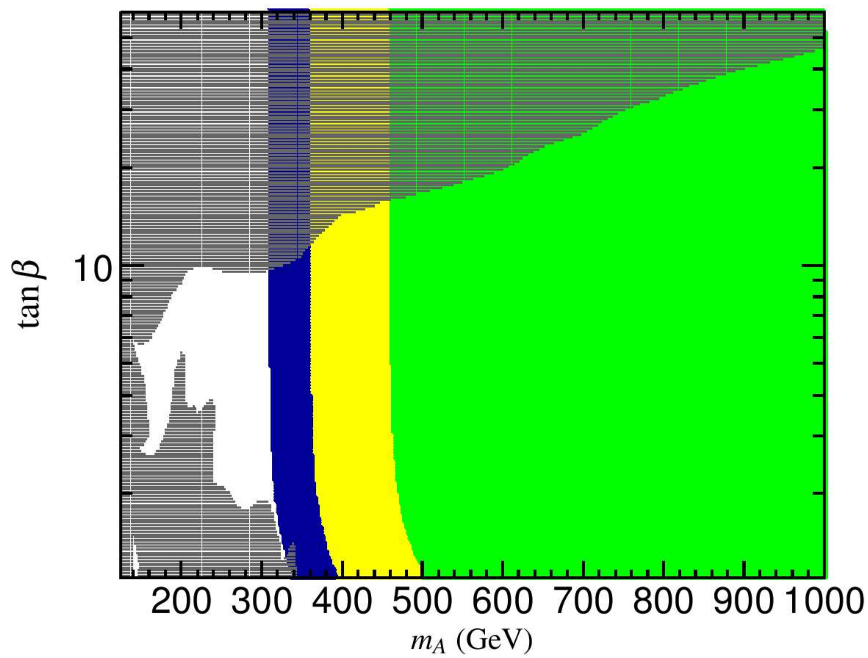




Direct constraints from LHC Higgs searches on the parameter space for the 2HDM Type-II with $m_H = 300$ GeV (left) and $m_H = 600$ GeV (right). The colors indicate compatibility with the observed Higgs signal at $1\,\sigma$ (green), $2\,\sigma$ (yellow) and $3\,\sigma$ (blue). Exclusion bounds at 95% C.L. from the non-observation of the additional Higgs states are overlaid in gray. The flipped Yukawa branch appears at larger values of $c_{\beta-\alpha}$.

Scenario G (MSSM-like)				
	m_h (GeV)	m_A (GeV)	$\tan\beta$	Type
G2	125	$90\ldots1000$	$1\ldots60$	II

Inspired by the MSSM Higgs potential, we take $\lambda_1 = \lambda_2 = \frac{1}{4}(g^2 + g'^2)$, $\lambda_3 = \frac{1}{4}(g^2 - g'^2)$, $\lambda_4 = -\frac{1}{2}g^2$, $\lambda_5 = \lambda_6 = \lambda_7 = 0$, and $m_{12}^2 = m_A^2 s_\beta c_\beta$. Simulating the largest MSSM radiative correction, we then shift $\lambda_2 \to \lambda_2 + \delta$ and choose δ to fix $m_h = 125$ GeV.



Allowed parameter space by direct Higgs search constraints in the "MSSM-like" Type-II 2HDM. The colors indicate compatibility with the observed Higgs signal at $1\,\sigma$ (green), $2\,\sigma$ (yellow) and $3\,\sigma$ (blue). Exclusion bounds at 95% C.L. from the non-observation of the additional Higgs states are overlaid in gray.