LHC Benchmarks for the CP-conserving Two-Higgs-Doublet Model (2HDM)

This work is based on

1. H.E. Haber and O. Stål, *New Benchmarks for the CP-conserving Two-Higgs-Doublet Model*, arXiv:1507.xxxxx

2. J. Bernon, J.F. Gunion, H.E. Haber, Y. Jiang and S. Kraml, *Scrutinizing the Alignment Limit in Two-Higgs-Doublet Models*, arxiv:1507.yyyyy

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1 July 2015

Outline

I. Higgs physics after discovery
   - What is the current data telling us?
   - Toward the Standard Model (SM)-like Higgs boson

II. The Two Higgs Doublet Model as a prototype for an extended Higgs sector
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The Higgs boson discovered on the 4th of July 2012

- Is it the Higgs boson of the Standard Model?

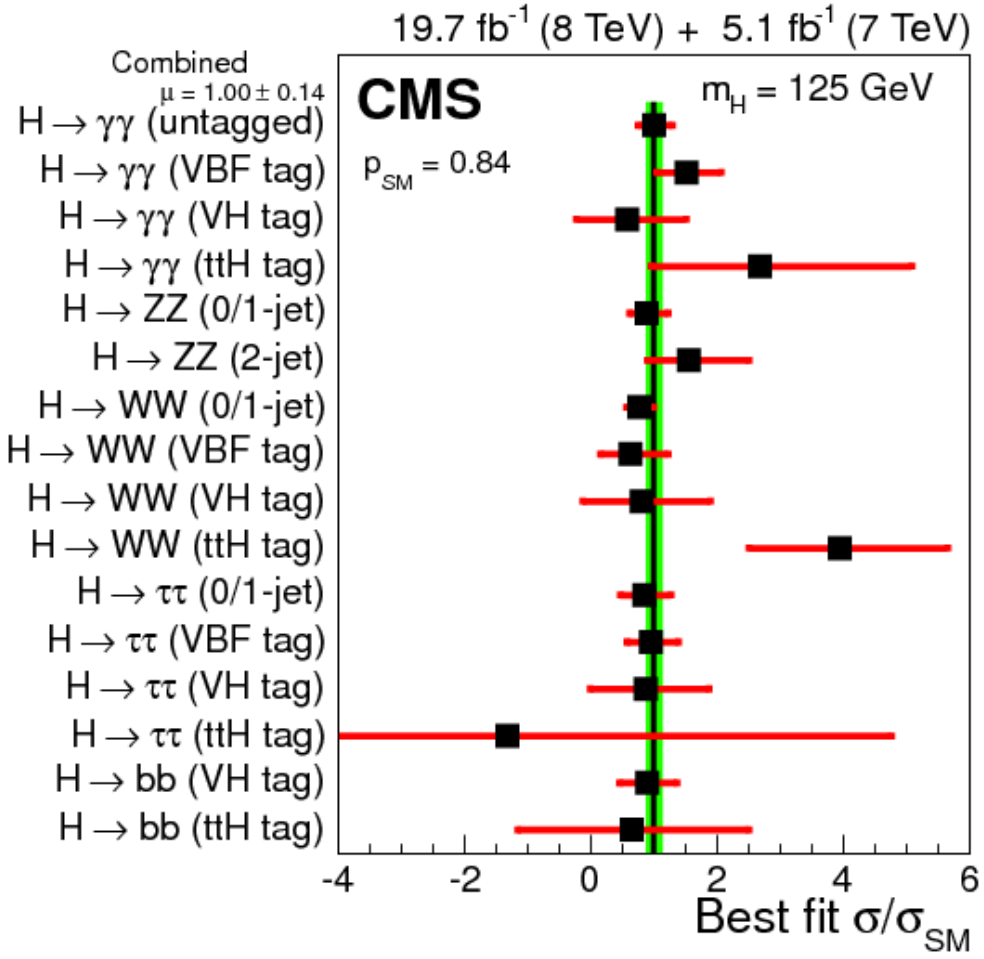
- Is it the first scalar state of an enlarged Higgs sector?

- Is it a premonition for new physics beyond the Standard Model at the TeV scale?

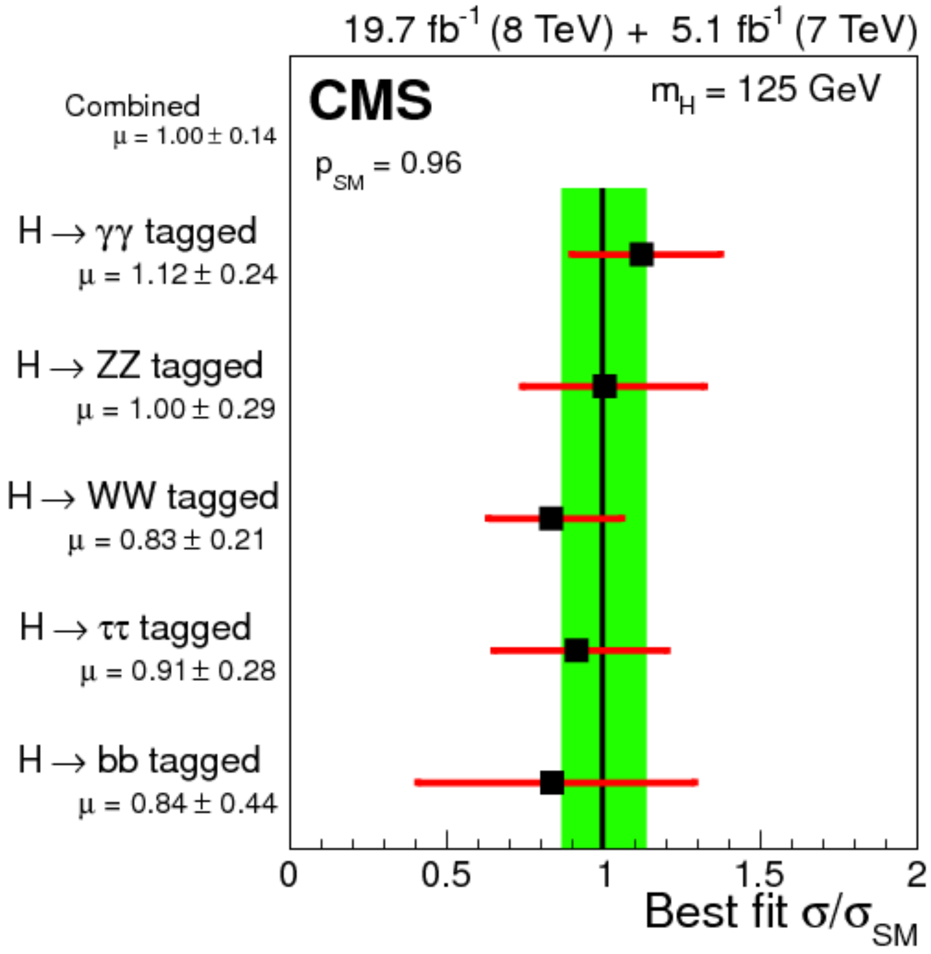
Let's look at a snapshop of the current LHC Higgs data.

m_H =125.09±0.21(stat.)±0.11(syst.) GeV

Evidence for a Standard Model (SM)—like Higgs boson



Values of the best-fit σ/σ_{SM} for the combination (solid vertical line) and for subcombinations by predominant decay mode and additional tags targeting a particular production mechanism. The vertical band shows the overall σ/σ_{SM} uncertainty. The σ/σ_{SM} ratio denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The horizontal bars indicate the ±1 standard deviation uncertainties in the best-fit σ/σ_{SM} values for the individual modes; they include both statistical and systematic uncertainties. Taken from Eur. Phys. J**. C75** (2015) 212**.**



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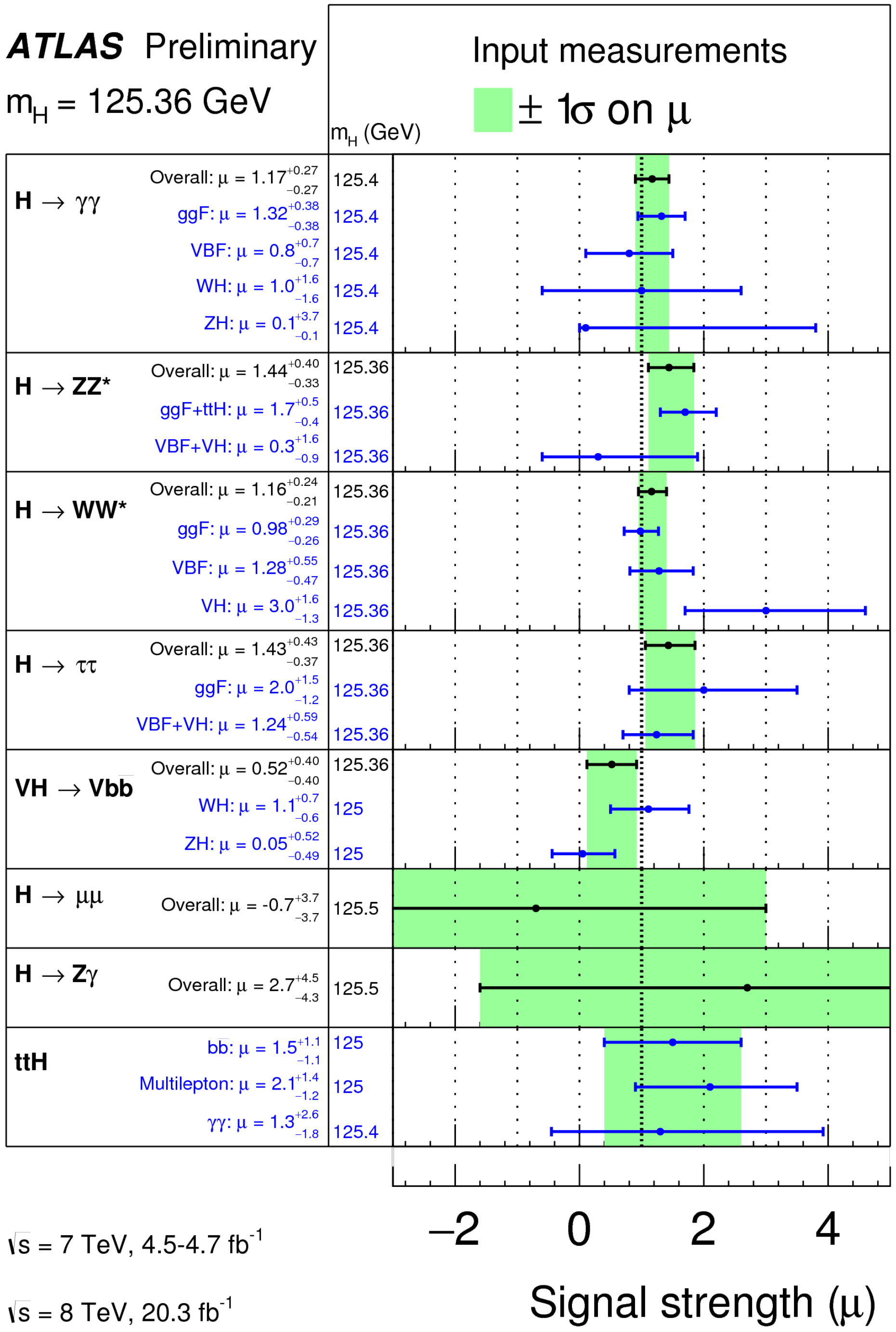
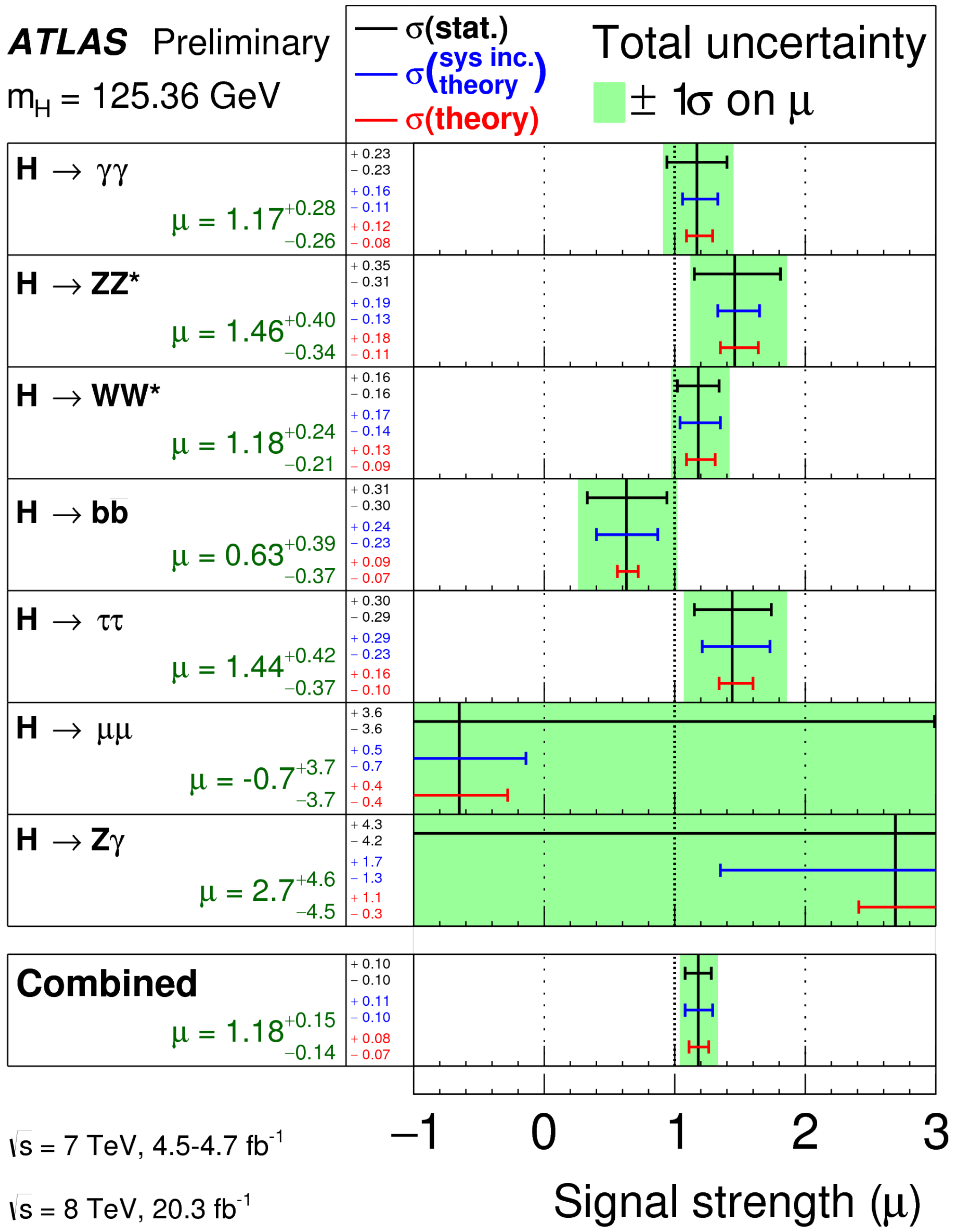




Taken from ATLAS-CONF-2015-007

Any theory that introduces new physics beyond the Standard Model (SM) must contain a SM-like Higgs boson. This constrains all future model building.

Motivations for an extended Higgs sector

- Theories that go beyond the SM often contain additional scalars
    - Example: the MSSM Higgs sector consists of two complex doublets of scalar fields
- Fermions appear in multiple generations, so why not additional Higgs doublets as well?
    - Ultimately, this must be decided by experiment.

The Two-Higgs Doublet Model (2HDM) as a prototype for an extended Higgs sector

The 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 observed experimental constraints.

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

By imposing the (softly-broken) $\mathbb{Z}_2$ symmetry, $\Phi_1 \to +\Phi_1\,;\ \Phi_2 \to -\Phi_2$, the resulting 2HDM naturally has no tree-level Higgs-mediated FCNCs. If we further assume that the scalar potential $\mathcal{V}$ is CP-conserving, then

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

where m_{12}^2 softly breaks the $\mathbb{Z}_2$ symmetry. That is, the hard $\mathbb{Z}_2$ symmetry-breaking term, $(\Phi_1^\dagger\Phi_2)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_2^\dagger\Phi_2) + \text{h.c.}$, is absent.

<u>Note</u>: we assume that the parameters m_{12}^2 and λ_5 are real and take on values that are consistent with a CP-conserving vacuum, in which case the vevs,

$$v_1 \equiv v\cos\beta\,, \qquad\qquad v_2 \equiv v\sin\beta\,,$$

can be chosen real and non-negative. In this convention, $\tan\beta \equiv v_2/v_1$ is non-negative (i.e. $0 \leq \beta \leq \frac{1}{2}\pi$).

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. Extending the non-trivial $\mathbb{Z}_2$ symmetry transformations to the right-handed fermion fields 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*:

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \Phi_1 c_\beta + \Phi_2 s_\beta \,, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv -\Phi_1 s_\beta + \Phi_2 c_\beta \,,$$

in terms of the scalar fields $\Phi_{1,2}$ of the $\mathbb{Z}_2$-basis. Here, $s_\beta \equiv \sin\beta$, $c_\beta \equiv \cos\beta$, etc. It follows that $\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$. The scalar potential is:

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

Under the assumption of a CP-conserving scalar potential and vacuum, all scalar potential parameters (Y_i and Z_i) can be taken real by a rephasing of H_2. By fixing a convention where $\tan\beta$ is non-negative, the values of the Y_i and Z_i are now uniquely defined.

After minimizing the scalar potential, $Y_1 = -\frac{1}{2}Z_1 v^2$ and $Y_3 = -\frac{1}{2}Z_6 v^2$.

The Z_i $(i = 1, \ldots, 7)$ are linear combinations of the λ_i $(i = 1, \ldots, 5)$.

$$
\begin{aligned}
Z_1 &\equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \tfrac{1}{2}\lambda_{345} s_{2\beta}^2 \,, \\
Z_2 &\equiv \lambda_1 s_\beta^4 + \lambda_2 c_\beta^4 + \tfrac{1}{2}\lambda_{345} s_{2\beta}^2 \,, \\
Z_i &\equiv \tfrac{1}{4} s_{2\beta}^2 \big[\lambda_1 + \lambda_2 - 2\lambda_{345}\big] + \lambda_i \,, \quad \text{(for } i = 3, 4 \text{ or } 5) \,, \\
Z_6 &\equiv -\tfrac{1}{2} s_{2\beta} \big[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta}\big] \,, \\
Z_7 &\equiv -\tfrac{1}{2} s_{2\beta} \big[\lambda_1 s_\beta^2 - \lambda_2 c_\beta^2 + \lambda_{345} c_{2\beta}\big] \,,
\end{aligned}
$$

where $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$. Since there are five nonzero λ_i and seven nonzero Z_i, there must be two relations. The following two identities are satisfied,

$$
\begin{aligned}
Z_2 &= Z_1 + 2(Z_6 + Z_7)\cot 2\beta \,, \\
Z_{345} &= \tfrac{1}{2}(Z_1 + Z_2) + 2(Z_6 - Z_7)\cot 4\beta \,,
\end{aligned}
$$

where $Z_{345} \equiv Z_3 + Z_4 + Z_5$.

Physical Higgs mass spectrum

The Higgs spectrum consists of two CP-even scalars, h and H (with $m_h \leq m_H$), one CP-odd scalar A and a charged Higgs pair $H^\pm$. The corresponding squared-masses of $H^\pm$ and A are

$$m^2_{H^\pm} = Y_2 + \tfrac{1}{2}Z_3 v^2\,, \qquad\qquad m^2_A = m^2_{H^\pm} + \tfrac{1}{2}(Z_4 - Z_5)v^2\,.$$

The CP-even scalars are identified by diagonalizing the 2×2 squared mass matrix,

$$\mathcal{M}^2_H = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}\,.$$

In the Higgs basis, the mixing angle that diagonalizes the above matrix is denoted by $\alpha - \beta$. That is, the physical CP-even mass eignestates are:

$$H = (\sqrt{2}\,\mathrm{Re}\,H_1^0 - v)c_{\beta-\alpha} - \sqrt{2}\,\mathrm{Re}\,H_2^0 s_{\beta-\alpha}\,,$$
$$h = (\sqrt{2}\,\mathrm{Re}\,H_1^0 - v)s_{\beta-\alpha} + \sqrt{2}\,\mathrm{Re}\,H_2^0 c_{\beta-\alpha}\,.$$

The following results will prove useful:

$$
\begin{aligned}
Z_1 v^2 &= m_h^2 s_{\beta-\alpha}^2 + m_H^2 c_{\beta-\alpha}^2\,, \\
Z_6 v^2 &= (m_h^2 - m_H^2) s_{\beta-\alpha} c_{\beta-\alpha}\,, \\
m_A^2 + Z_5 v^2 &= m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2\,,
\end{aligned}
$$

which relates Z_1, Z_5 and Z_6 directly to the physical scalar masses and the mixing angle $\beta - \alpha$. Note that the second equation above implies that

$$
Z_6 s_{\beta-\alpha} c_{\beta-\alpha} \leq 0.
$$

The sign of Z_6 is meaningful in a convention where $\tan\beta$ is non-negative [since one cannot make a field redefinition $H_2 \to -H_2$]. Since the mass eigenstate fields h and H are only defined up to an overall sign, the mixing angle $\beta - \alpha$ is only defined modulo π. It is convenient to choose $0 \leq \beta - \alpha \leq \pi$ so that $s_{\beta-\alpha}$ is non-negative, in which case the sign of $c_{\beta-\alpha}$ is equal to $-\text{sgn}\, Z_6$.

The alignment limit

Let us revisit the CP-even Higgs squared-mass matrix,

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} .$$

Since the Higgs basis fields satisfy $\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$, the couplings of H_1 are precisely those of the Standard Model (SM). Thus, in the *alignment limit*, a SM-like Higgs boson exists which is roughly aligned with $\sqrt{2}\,\mathrm{Re}\,H_1^0 - v$. That is, the mixing of H_1^0 and H_2^0 is subdominant, which implies that either

1. $|Z_6| \ll 1$, and/or

2. $m_A^2 \gg Z_i v^2$ for $i = 1, 5$ and 6, corresponding to the *decoupling limit*.

Moreover, if in addition $Z_1 v^2 < m_A^2 + Z_5 v^2$, then h is SM-like, whereas if $Z_1 v^2 > m_A^2 + Z_5 v^2$, then H is SM-like. In both cases, the squared-mass of the SM-like Higgs boson is approximately equal to $Z_1 v^2$.

Case 1: A SM-like h, with $m_h \simeq 125$ GeV

Noting that the coupling of h to VV (where $V = W^\pm$ or Z) relative to that of the SM Higgs boson $h_{\rm SM}$ is given by $g_{hVV}/g_{h_{\rm SM}VV} = s_{\beta-\alpha}$. It follows that h is SM-like if $s_{\beta-\alpha}$ is close to 1, in which case $|c_{\beta-\alpha}| \ll 1$. The formulae,

$$m_h^2 = \left(Z_1 + Z_6 \frac{c_{\beta-\alpha}}{s_{\beta-\alpha}}\right) v^2 \,,$$

and

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

exhibit the expected properties of the alignment limit, which is achieved if $|Z_6| \ll 1$ and/or $m_H \gg m_h$. In either case, we have $m_h^2 \simeq Z_1 v^2$.

The case of $m_H \gg m_h$ is the well known decoupling limit, where the squared mass differences between non-SM Higgs states $H^\pm$, H and A are of $\mathcal{O}(v^2)$. But, the interesting possibility of *alignment without decoupling* arises if $|Z_6| \ll 1$. In this case, h is SM-like and yet the non-SM-like Higgs states might not be all that much heavier than h.

Case 2: A SM-like H with $m_H \simeq 125$ GeV

Noting that the coupling of H to VV is given by $g_{HVV}/g_{h_{\rm SM}VV} = c_{\beta-\alpha}$. In this case, it is more useful to adopt a convention where $c_{\beta-\alpha}$ is non-negative, so that $s_{\beta-\alpha}$ can be of either sign. It follows that H is SM-like if $c_{\beta-\alpha}$ is close to 1, in which case $|s_{\beta-\alpha}| \ll 1$. The formulae,

$$m_H^2 = \left(Z_1 - Z_6 \frac{s_{\beta-\alpha}}{c_{\beta-\alpha}}\right) v^2 \,,$$

and

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

exhibit the expected properties of the alignment limit, which is achieved if $|Z_6| \ll 1$, in which case $m_H^2 \simeq Z_1 v^2$. Note that no decoupling limit exists here since the masses of H, A and $H^\pm$ are all of $\mathcal{O}(v)$.

Thus, the case of a SM-like H necessarily corresponds to the alignment limit without decoupling.

Higgs-fermion Yukawa couplings revisited

For simplicity, we consider only Type-I and Type-II Yukawa couplings.

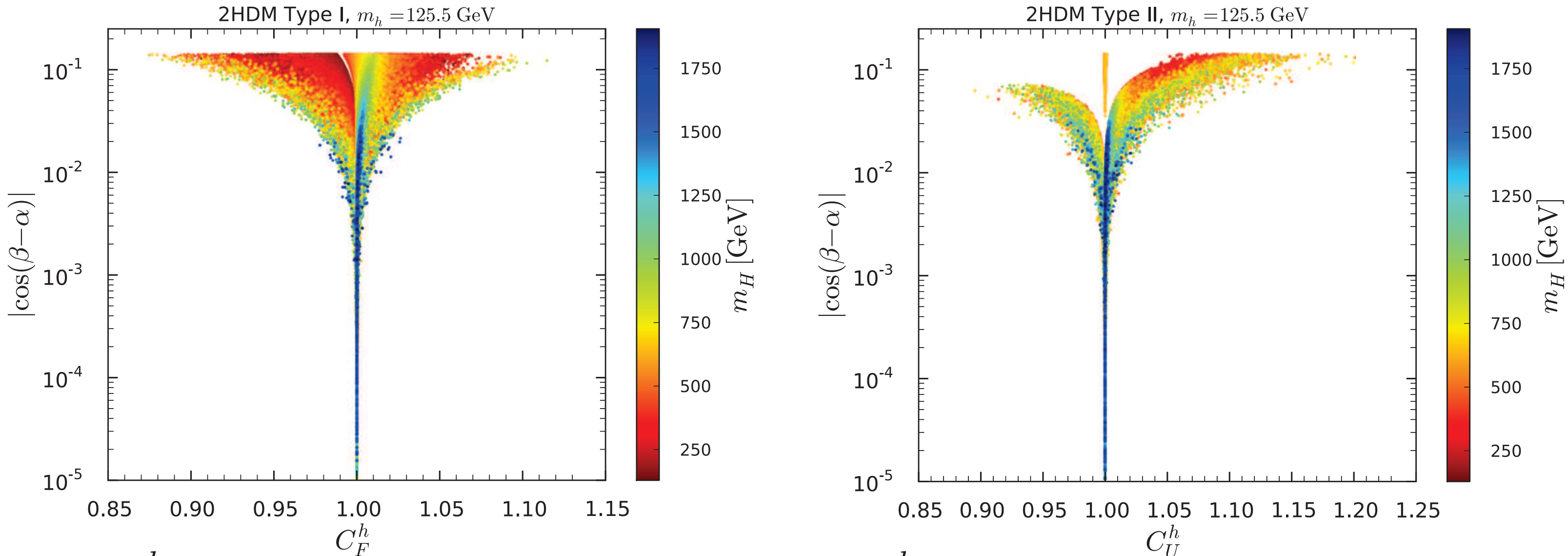
	Type I and II	Type I		Type II	
Higgs	VV	up quarks	down quarks and leptons	up quarks	down quarks and leptons
h	$s_{\beta-\alpha}$	c_α/s_β	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$
H	$c_{\beta-\alpha}$	s_α/s_β	s_α/s_β	s_α/s_β	c_α/c_β
A	0	$\cot\beta$	$-\cot\beta$	$\cot\beta$	$\tan\beta$

It is sometimes more convenient to write the couplings of h to fermions as

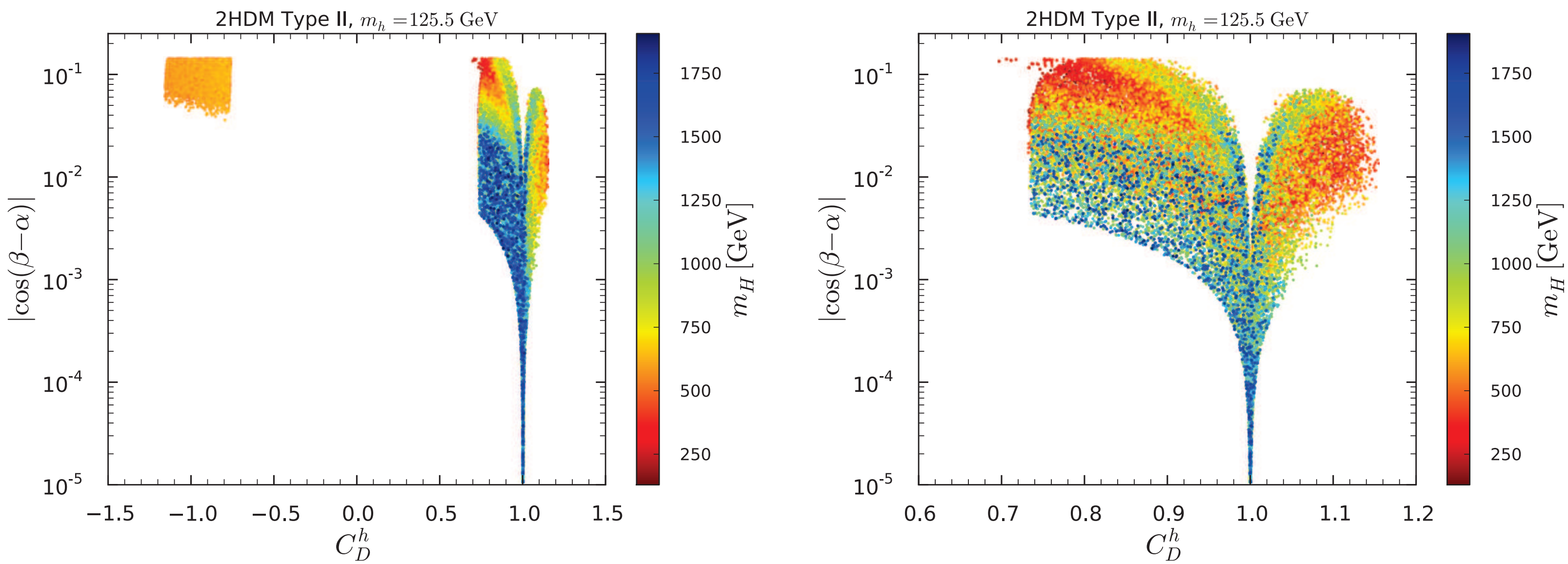
$$c_\alpha/s_\beta = s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta\,,$$

$$-s_\alpha/c_\beta = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta\,,$$

In the limit of $|c_{\beta-\alpha}| \ll 1$, the h couplings approach their SM values, although the approach to alignment is *delayed* if, e.g., $|c_{\beta-\alpha}|\tan\beta \sim \mathcal{O}(1)$.



$|c_{\beta-\alpha}|$ versus C_F^h ($F = U$ or D) in Type I (left) and $|c_{\beta-\alpha}|$ versus C_U^h in Type II (right) with m_H color code. The points with $C_U^h \approx 1$ and $|c_{\beta-\alpha}| > 0.03$ are the points for which $C_D^h \approx -1$ (the so-called opposite-sign Yukawa coupling points).



$|c_{\beta-\alpha}|$ versus C_D^h in Type II with m_H color code for the full C_D^h range (left) and zooming on the $C_D^h > 0$ region (right). Points are ordered from low to high m_H in both sets of plots above.

Trilinear Higgs self-couplings

A few examples:

$$\begin{aligned} g_{hhh} &= -3v\big[Z_1 s^3_{\beta-\alpha} + Z_{345} s_{\beta-\alpha} c^2_{\beta-\alpha} + 3Z_6 c_{\beta-\alpha} s^2_{\beta-\alpha} + Z_7 c^3_{\beta-\alpha}\big]\,, \\ g_{Hhh} &= -3v\big[Z_1 c_{\beta-\alpha} s^2_{\beta-\alpha} + Z_{345} c_{\beta-\alpha}\left(\tfrac{1}{3} - s^2_{\beta-\alpha}\right) \\ &\qquad -Z_6 s_{\beta-\alpha}(1-3c^2_{\beta-\alpha}) - Z_7 c^2_{\beta-\alpha} s_{\beta-\alpha}\big]\,, \\ g_{hH^+H^-} &= -v\big[Z_3 s_{\beta-\alpha} + Z_7 c_{\beta-\alpha}\big]\,, \end{aligned}$$

Suppose that h is SM-like. Then, to study the behavior in the alignment limit where $|c_{\beta-\alpha}| \ll 1$, it is convenient to write $c_{\beta-\alpha} = -\eta Z_6$, where

$$\eta \equiv \frac{v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}} = \begin{cases} \mathcal{O}(1)\,, & \text{for } m_H^2 \sim \mathcal{O}(v^2), \\ \mathcal{O}\left(\dfrac{v^2}{m_H^2}\right) \ll 1\,, & \text{in the decoupling limit.} \end{cases}$$

Then,

$$g_{hhh} = g_{hhh}^{\rm SM}\left\{1 + \left[\left(Z_{345} - \tfrac{3}{2}Z_1\right)\eta^2 - 2\eta\right]\frac{Z_6^2}{Z_1} + \mathcal{O}(\eta^3 Z_6^3) + \mathcal{O}(\eta^2 Z_6^4)\right\},$$

where $g_{hhh}^{\rm SM} \equiv -3m_h^2/v$. In the decoupling limit (where $\eta \ll 1$),

$$g_{hhh} = g_{hhh}^{\rm SM}\left\{1 - \frac{2\eta Z_6^2}{Z_1} + \mathcal{O}(\eta^2 Z_6^2)\right\}.$$

It follows that g_{hhh} is always suppressed with respect to the SM in the decoupling limit.

In contrast, in the alignment limit without decoupling, $|Z_6| \ll 1$ and $\eta \sim \mathcal{O}(1)$. In this case, in a region of parameter space where $Z_{345} \gg Z_1$ and $\eta Z_{345} \gg 1$, we find that g_{hhh} is enhanced with respect to the SM.

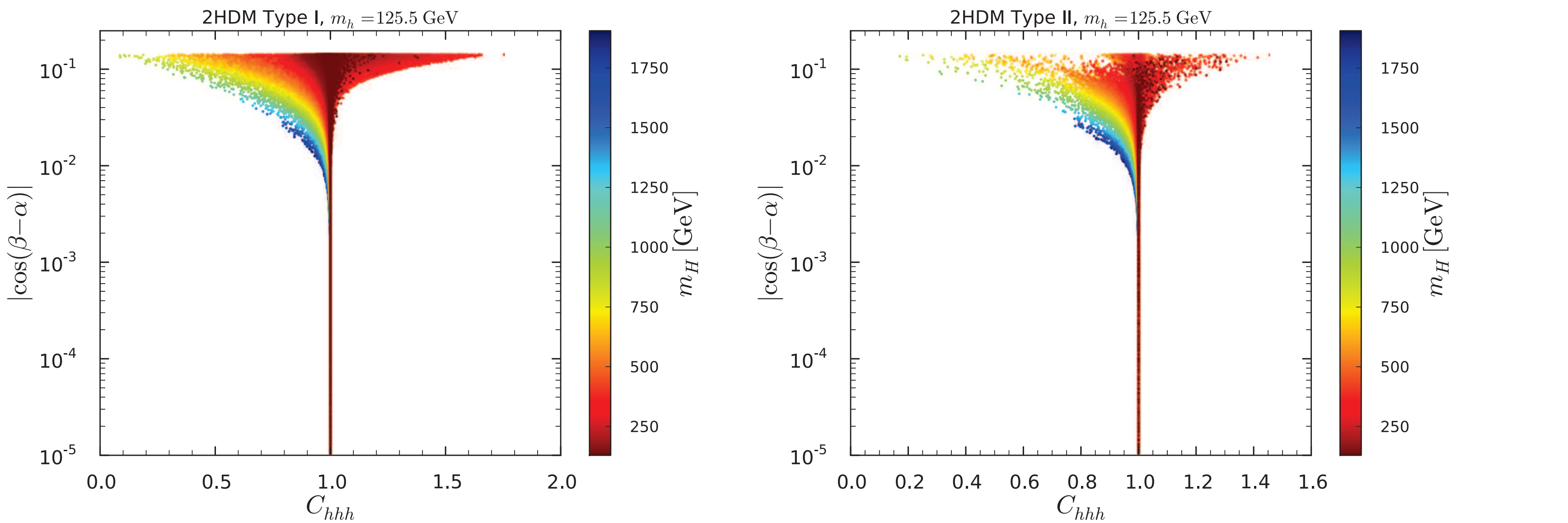
The Higgs self-couplings distinguish between the regime of alignment without decoupling and the decoupling regime due to the explicit appearance of Z_6 in the self-couplings.

Likewise, for the case of a SM-like h close to the alignment limit,

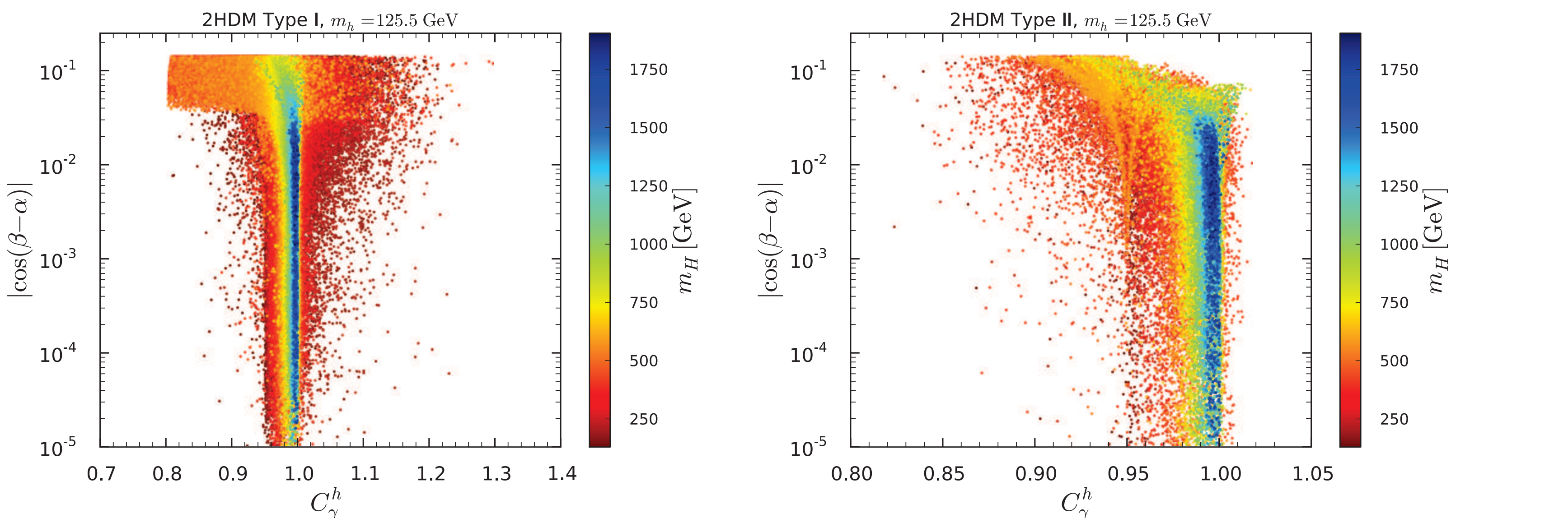
$$
\begin{aligned}
g_{Hhh} &= 3v\big[Z_6 - (Z_1 - \tfrac{2}{3}Z_{345})c_{\beta-\alpha} + \mathcal{O}(c^2_{\beta-\alpha})\big]\,, \\
g_{hH^+H^-} &= -v\big[Z_3 + \mathcal{O}(c_{\beta-\alpha})\big]\,.
\end{aligned}
$$

The Hhh coupling is suppressed in the alignment limit without decoupling, while it can be of $\mathcal{O}(v)$ in the decoupling limit.

The hH^+H^- is relevant for the one loop decay $h \to \gamma\gamma$, which has a contribution mediated by a $H^\pm$ loop. In the decoupling limit, the $H^\pm$ loop amplitude is suppressed by a factor of $\mathcal{O}(v^2/m^2_{H^\pm})$ relative to the $W^\pm$ and the top quark loop contributions. But, in the alignment limit without decoupling, the $H^\pm$ loop is parametrically of the same order as the corresponding SM loop contributions, thereby leading to a shift of the $h \to \gamma\gamma$ decay rate from its SM value (even though all tree-level couplings of h are SM-like).



Reduced triple Higgs coupling C_{hhh} versus m_H in Type I (left) and Type II (right) with m_H color code. Points are ordered from high to low m_H values.



$|c_{\beta-\alpha}|$ versus C^h_γ in Type I (left) and Type II (right) with m_H color code. Points are ordered from low to high m_H.

Hybrid strategy for specifying 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 include:

- 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 VV.
- Easy to implement theoretical constraints on parameters (e.g., perturbativity limits for the Z_i); useful for efficient 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).

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

$$m_A^2 = m_H^2 s^2_{\beta-\alpha} + m_h^2 c^2_{\beta-\alpha} - Z_5 v^2\,,$$

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

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

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

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

$$m_H = m_A \text{ and } c_{\beta-\alpha} = 0 \quad\Longrightarrow\quad Z_5 = 0\,.$$

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

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

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`.

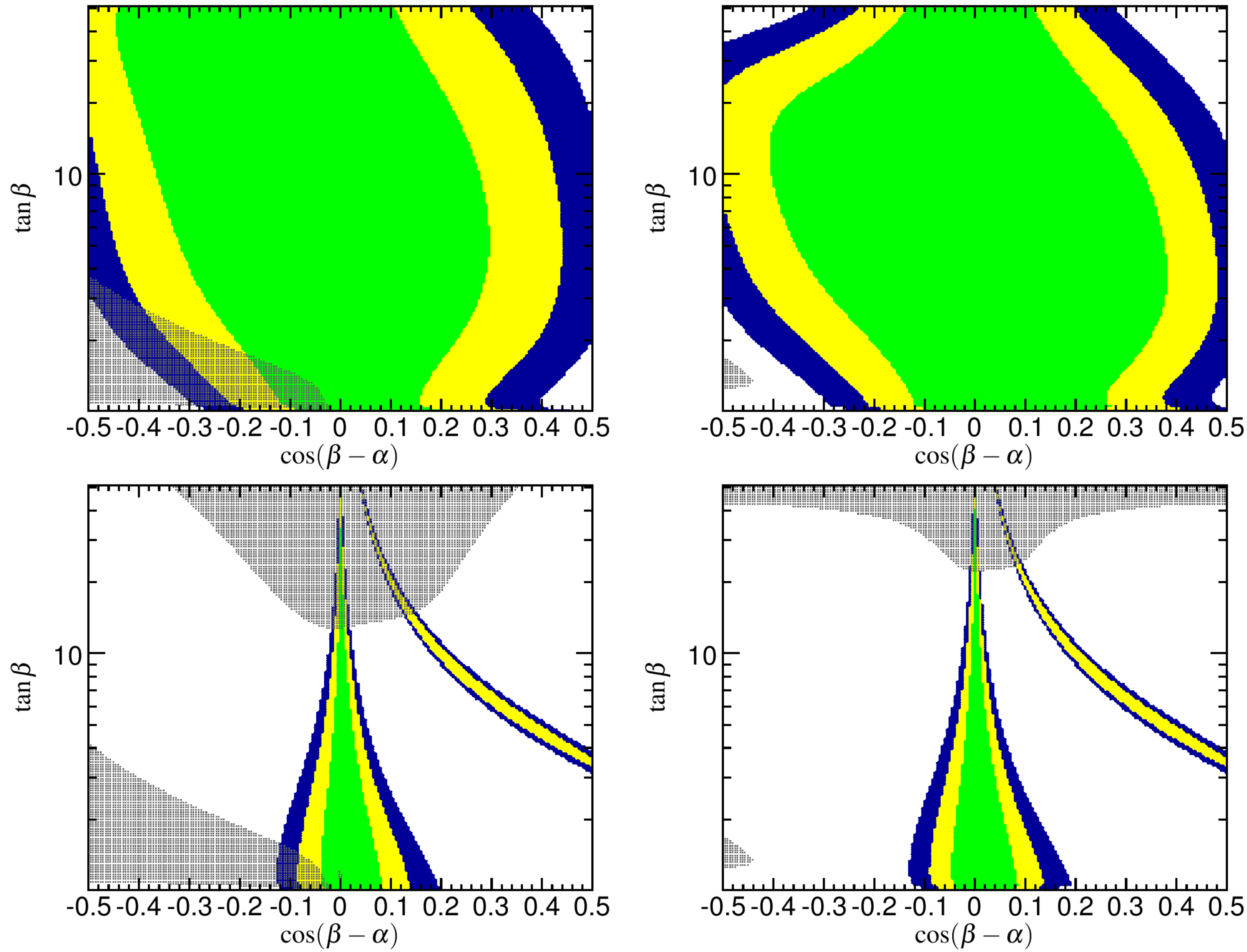
4. Implementing constraints due to the observation of a SM-like Higgs boson are evaluated using `HiggsSignals`.

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

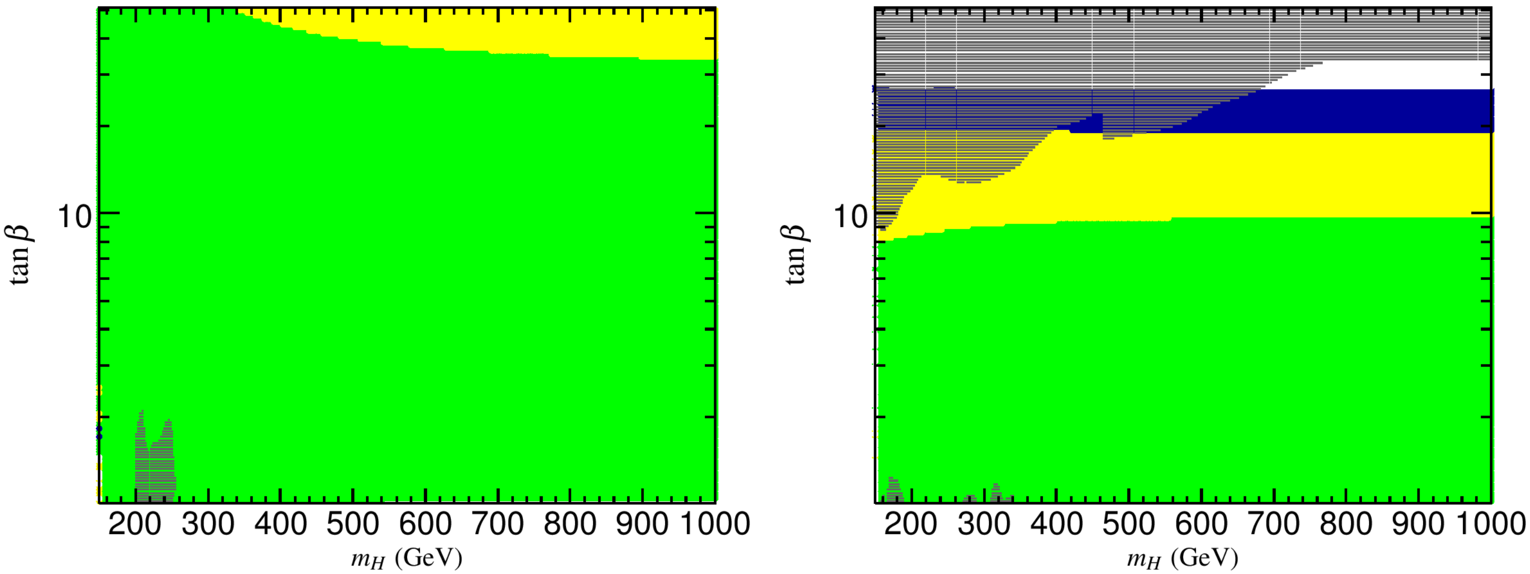
6. Flavor constraints apply in a pure 2HDM. The latest result of M. Misiak et al., Phys. Rev. Lett. **114**, 221801 (2015), based on the observed $b \to s\gamma$ rate yields $m_{H^\pm} \gtrsim 480$ GeV at 95% CL in a Type-II 2HDM.

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	$150\ldots600$	0.1	-2	-2	0	$1\ldots50$	I
A1.2	125	$150\ldots600$	$0.1\times\left(\frac{150\text{ GeV}}{m_H}\right)^2$	-2	-2	0	$1\ldots50$	I
A2.1	125	$150\ldots600$	0.01	-2	-2	0	$1\ldots50$	II
A2.2	125	$150\ldots600$	$0.01\times\left(\frac{150\text{ GeV}}{m_H}\right)^2$	-2	-2	0	$1\ldots50$	II

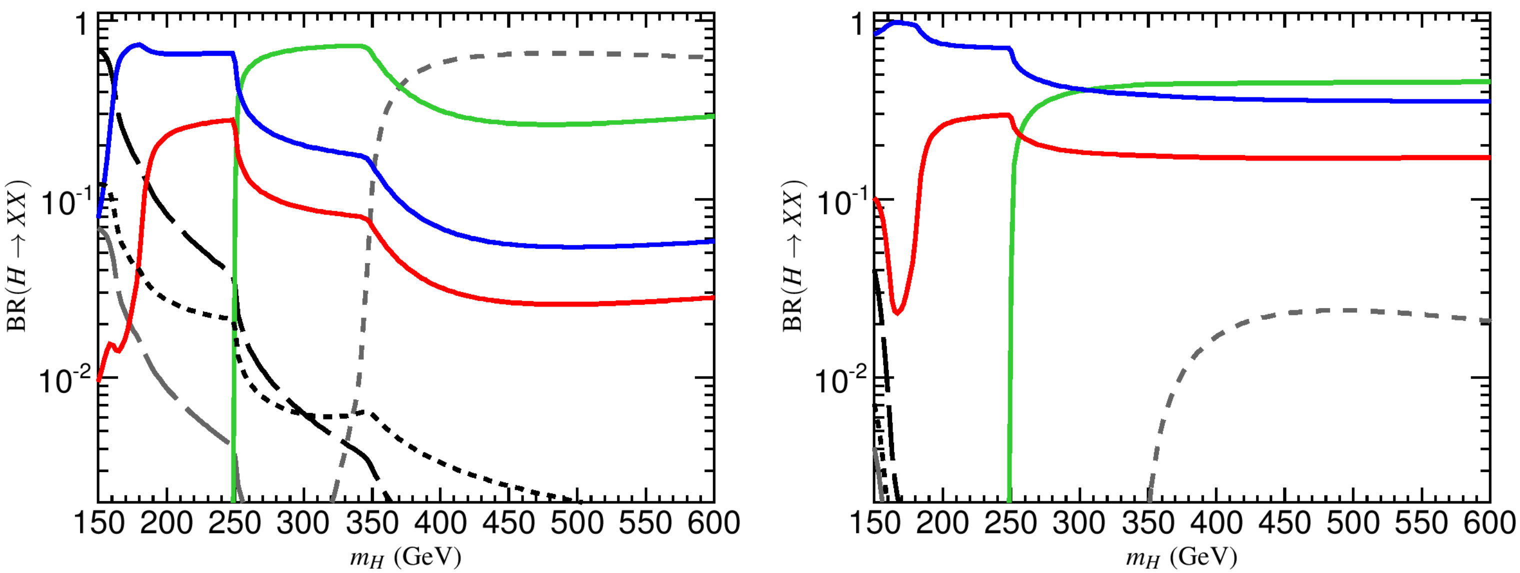
- These are "simplified models" where $m_h = 125\text{ GeV} < m_H < m_A = m_{H^\pm}$.
- All values of $\tan\beta$ allowed and $c_{\beta-\alpha} \lesssim 0.1$ in Type-I; $\tan\beta \lesssim 10$ favored and $c_{\beta-\alpha} \lesssim 0.01$ in Type-II.
- Cross sections are largest for low $\tan\beta$ (enhanced 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.



Direct constraints from LHC Higgs searches on the parameter space for the 2HDM Type-I (top) and Type-II (bottom) with $m_H = 300$ GeV (left) and $m_H = 600$ GeV (right). In both cases $m_h = 125$ GeV, $Z_4 = Z_5 = -2$ and $Z_7 = 0$. The colors indicate compatibility with the observed Higgs signal at $1\,\sigma$ (green), $2\,\sigma$ (yellow) and $3\,\sigma$ (blue). Exclusion bounds at 95% CL from the non-observation of the additional Higgs states are overlaid in gray.



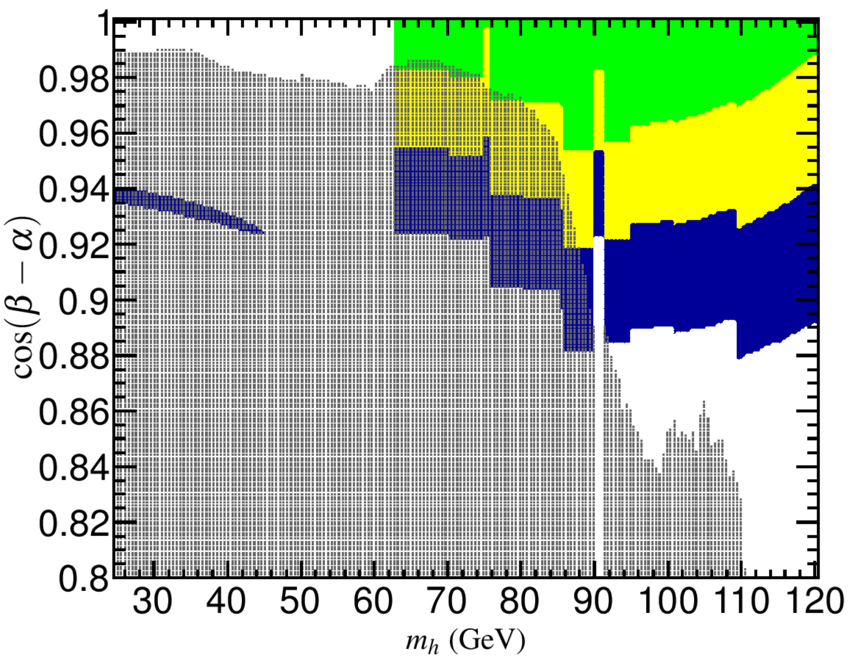
Parameter space of the non-aligned benchmark Scenario A with Type-I couplings, $c_{\beta-\alpha} = 0.1$ (left) and Type-II Yukawa couplings, $c_{\beta-\alpha} = 0.01$ (right). The color coding is the same as in the previous figure.

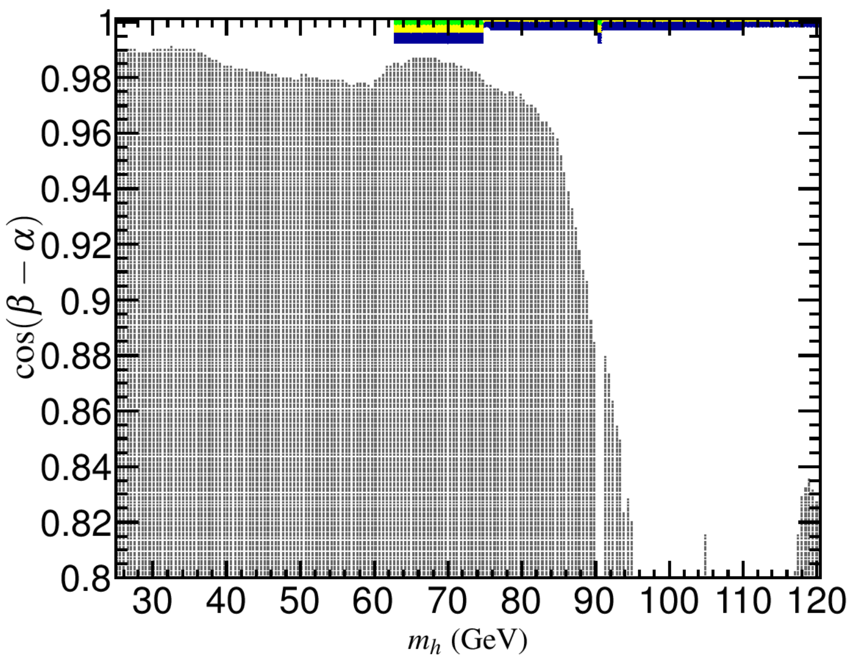


Branching ratios of the Heavy Higgs boson, H, in scenario A with Type-I couplings for $\cos(\beta-\alpha) = 0.1$, $\tan\beta = 1.5$ (left) and $\tan\beta = 7$ (right). Colors: $H \to W^+W^-$ (blue, solid), $H \to ZZ$ (red, solid), $H \to hh$ (green, solid), $H \to t\bar{t}$ (gray, short dash), $H \to b\bar{b}$ (black, long dash), $H \to \tau\tau$ (gray, long dash) and $H \to gg$ (black, short dash).

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

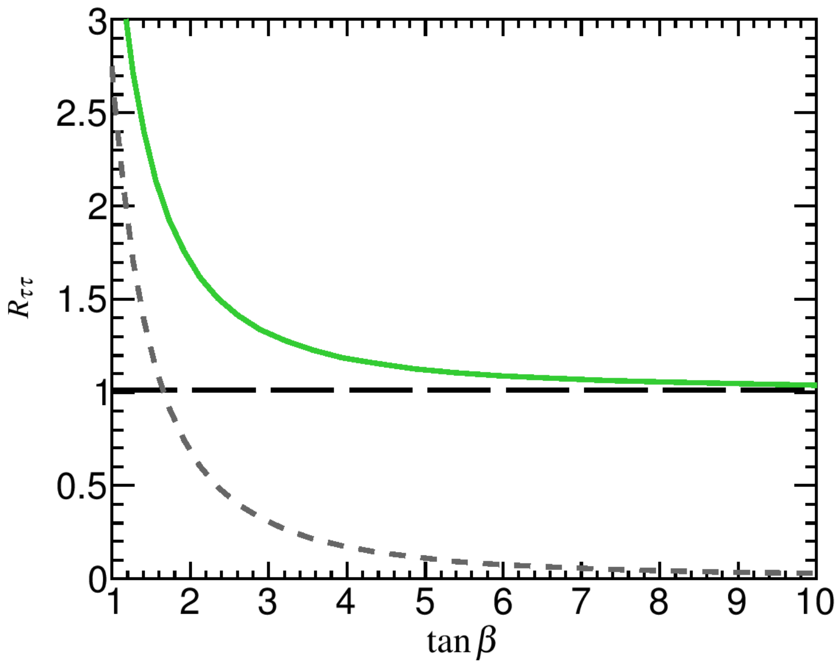
These are "simplified models" where $m_h < m_H = 125$ GeV $\ll m_A = m_{H^\pm}$.

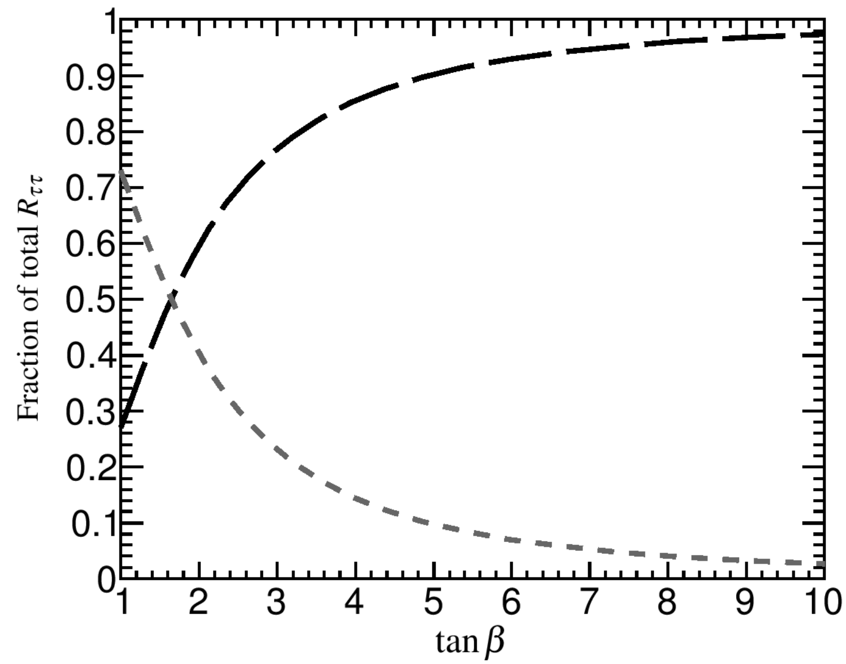




Allowed parameter regions for h in Scenario B with Type-I Yukawa couplings (left) and Type-II couplings (right). The colors indicate statistical compatibility with the 125 GeV Higgs signal at $1\,\sigma$ (green), $2\,\sigma$ (yellow) and $3\,\sigma$ (blue). The gray region is excluded at 95% C.L. by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



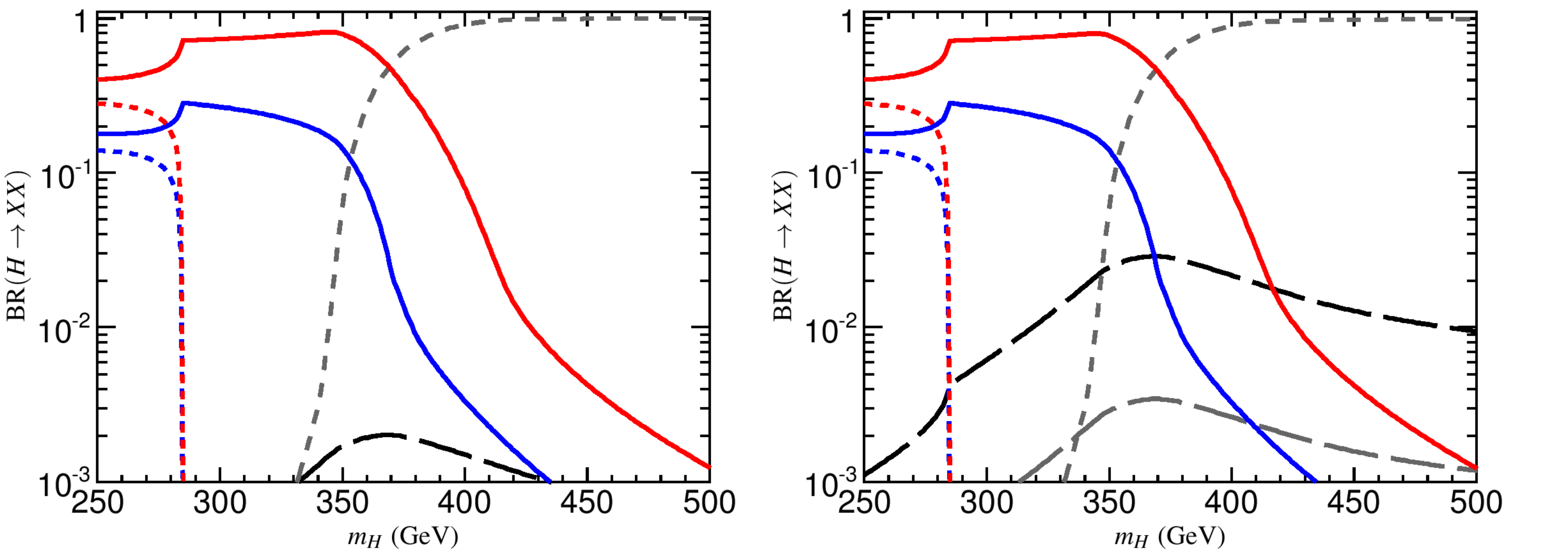


In Scenario C with Type-I Yukawa couplings , the total $\tau\tau$ rate (adding gg and $b\bar{b}$ production modes), relative to the SM, from h (long dashes), A (short dashes) and their sum (green, solid). Right: the respective fractions of the inclusive $\tau\tau$ rate resulting from h (long dashes)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

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)	mass hierarchy	Z_4	Z_5	Z_7	$\tan\beta$	Type
D(1,2).1	$250\ldots500$	$m_A < m_H = m_{H^\pm}$	-1	1	-1	2	I, II
D(1,2).2	$250\ldots500$	$m_{H^\pm} < m_H = m_A$	2	0	-1	2	I, II
D(1,2).3	$250\ldots500$	$m_A = m_{H^\pm} < m_H$	1	1	-1	2	I, II

In all cases above, $m_h = 125$ GeV and $\cos(\beta-\alpha) = 0$.



Branching ratios of H in Scenarios D(1,2).3 with $m_A = m_{H^\pm} < m_H$ 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 of the non-SM-like Higgs bosons.
- Competing decays: $H^{\pm} \to AW^{\pm} \to HZW^{\pm}$ and $H^{\pm} \to W^{\pm}H$.
- Competing decays: $A \to H^{\pm}W^{\mp} \to HW^{+}W^{-}$ and $A \to ZH$
- Branching ratios for two step decays are typically in the range of 1–5%.

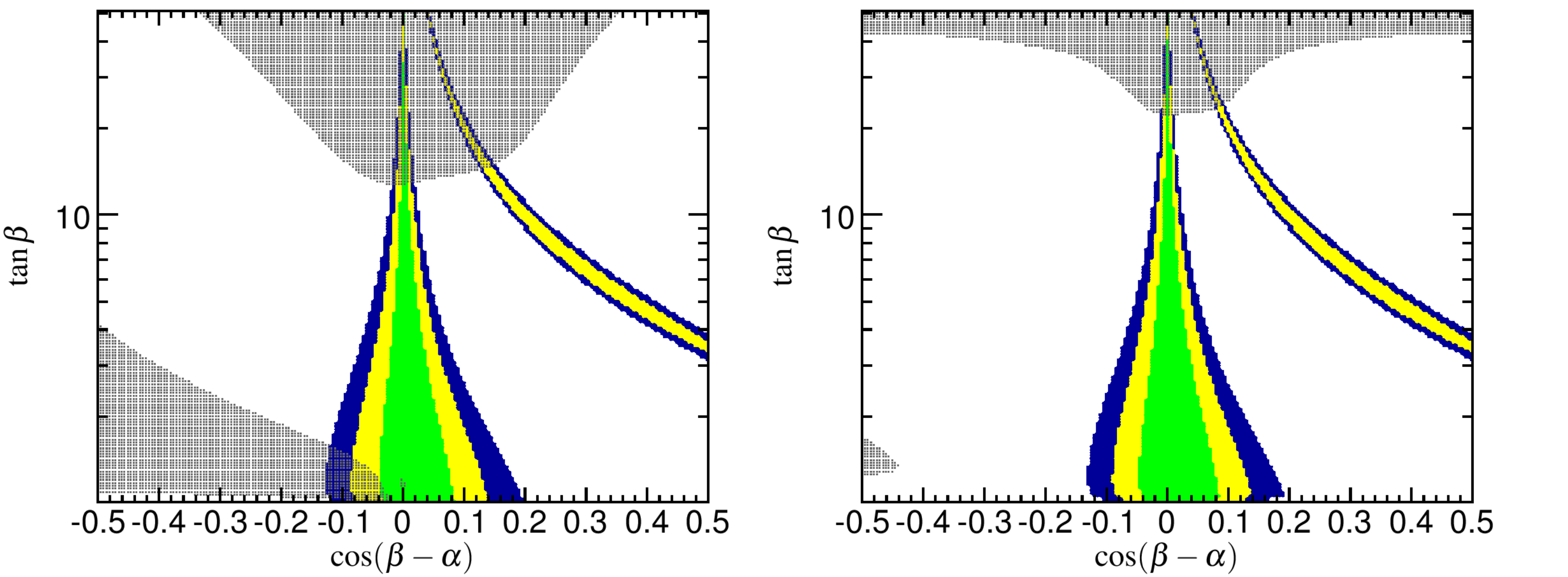
	Masses (GeV)			Branching ratios			
Scenario	m_H	m_A	$m_{H^\pm}$	$H^{\pm} \to W^{\pm}A$	$H^{\pm} \to W^{\pm}\ H$	$A \to ZH$	$A^{\pm} \to W^{\pm}H^{\mp}$
E1	200	402	532	0.053	0.79	0.62	–
	300	460	577	0.041	0.74	0.39	–
E2	200	471	317	–	0.27	0.56	0.25
	300	521	388	–	0.026	0.50	0.20

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	$150\dots600$	$\sin 2\beta$	-2	-2	0	$5\dots50$	II

As in Scenario A, we take $m_h < m_H < m_A = m_{H^\pm}$. However, we fix $c_{\beta-\alpha} = s_{2\beta}$ so that

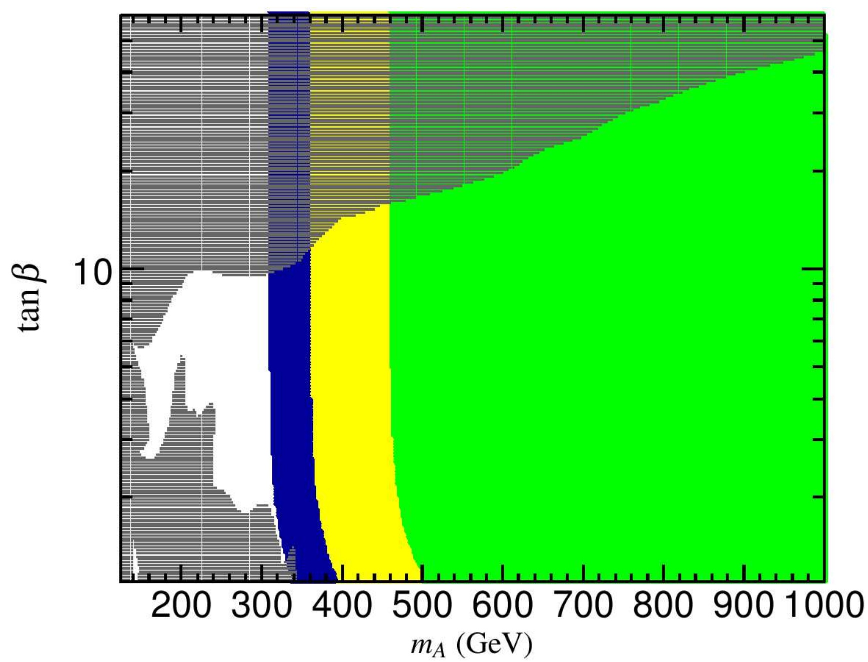
$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta = -1.$$



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% CL 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% CL from the non-observation of the additional Higgs states are overlaid in gray.

Scenario H: The Inert 2HDM (IDM)

If $Z_6 = Z_7 = 0$, then the minimum condition enforces $Y_3 = 0$. In this case the $\mathbb{Z}_2$ symmetry is manifest in the Higgs basis and it is unbroken by the vacuum. If in addition we employ Type-I Yukawa couplings, then under a $\mathbb{Z}_2$ symmetry transformation, H_2 is odd and all other relevant fields (H_1 and all left and right handed fermion fields) are even.

Hence, either $c_{\beta-\alpha} = 0$ (and h is the SM Higgs boson) or $s_{\beta-\alpha} = 0$ (and H is the SM Higgs boson). This is the *exact* alignment limit. The two other neutral Higgs bosons, denoted arbitrarily by H_I and A_I obey the following mass relations,

$$m^2_{A_I} = m^2_{H_I} - Z_5 v^2 \,, \qquad\qquad m^2_{H^\pm} = m^2_{H_I} - \tfrac{1}{2}(Z_4 + Z_5)v^2 \,.$$

However, there is no measurement that can determine the separate CP quantum numbers of H_I and A_I (although they are *relatively* CP-odd). The lighter of these two states can serve as a candidate for stable dark matter.

Future Directions

From purely phenomenological considerations, the softly-broken $\mathbb{Z}_2$-symmetric CP-conserving 2HDM is more constrained than necessary. In order to avoid tree-level Higgs-mediated FCNCs, it is sufficient to have (approximate) "flavor-aligned" Higgs-fermion Yukawa interactions. Although such a model requires an extra fine-tuning of parameters, it is not presently in conflict with data.

Thus, to be more general, one should not impose any discrete (or continuous) symmetries on the scalar potential nor require CP-invariance.* In this more general case, all the λ_i appear. Note that the λ_i are basis-dependent (as is $\tan\beta$), which implies that these parameters are unphysical. However, the parameters of the Higgs basis and the neutral Higgs mixing angles computed in the Higgs basis are physical physical parameters (up to a possible rephasing ambiguity).

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*Ultimately, we would like experiment to decide whether these features are present in nature.

Thus, the methods of this work can be easily extended to the case of a more general flavor-aligned 2HDM.

- The conditions of the alignment limit are easily obtained.

- The hybrid strategy for specifying input parameters would then consist of

$$\{m_h, m_{H^\pm}, s_{12}, s_{13}, Z_i, \alpha_i\},$$

  where the Z_i represent a set of Higgs basis parameters not constrained by the first four parameters listed above, the α_i are flavor alignment parameters, and s_{12} and s_{13} are two mixing angles that emerge from the diagonalization of the neutral Higgs squared mass matrix [details can be found in H.E. Haber and D. O'Neil, Phys.. Rev. **D74**, 015018 (2016)].