Higgs Alignment and CP Violation

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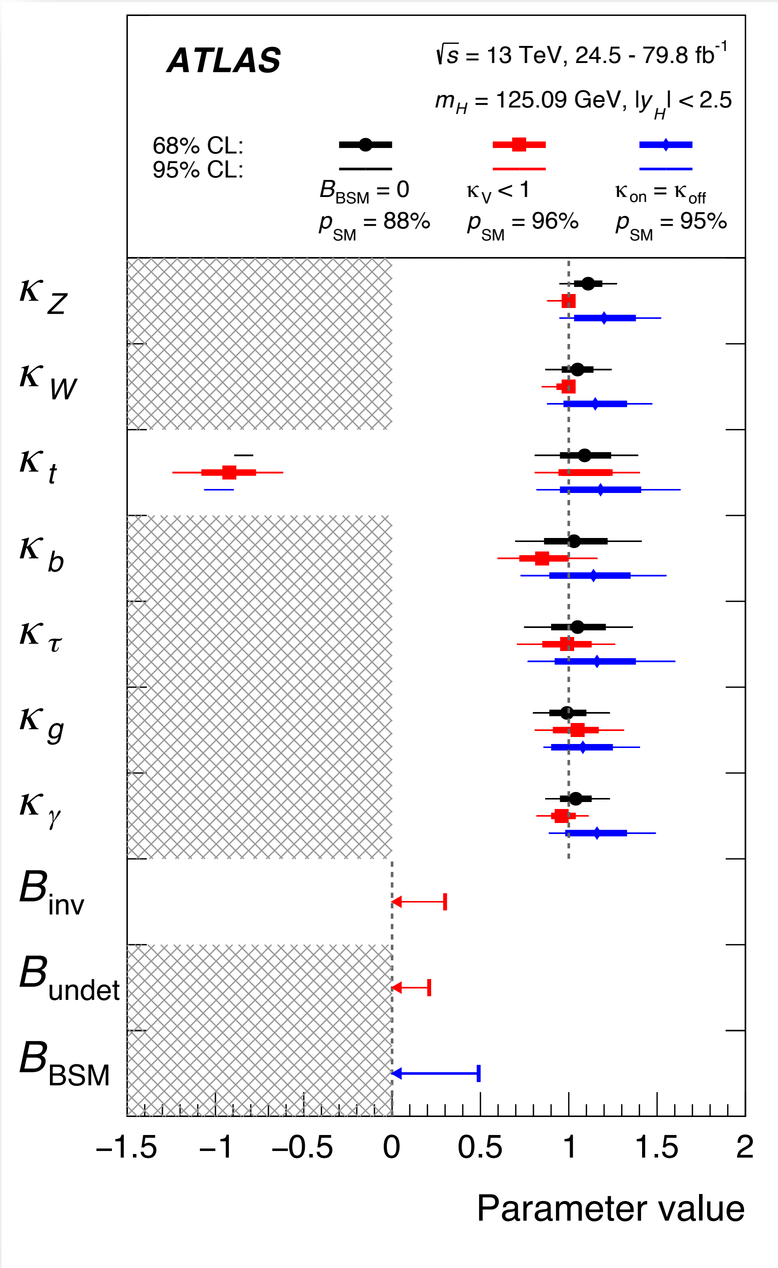
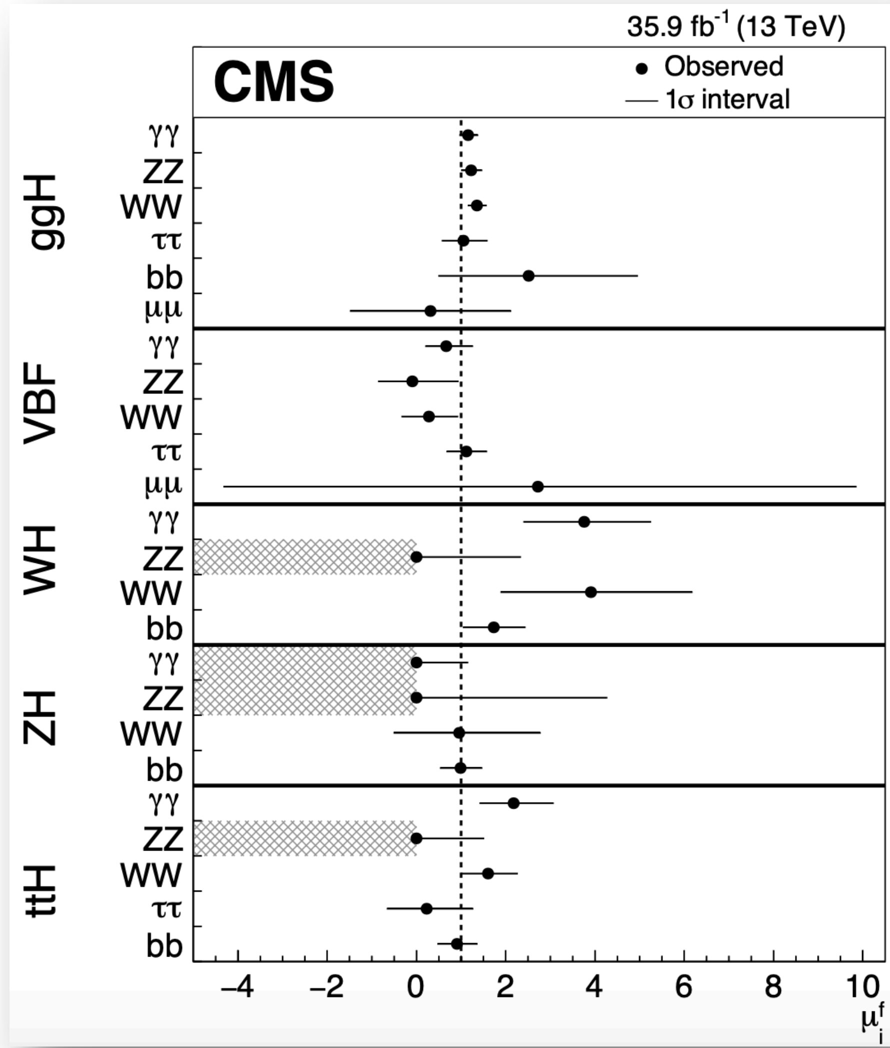
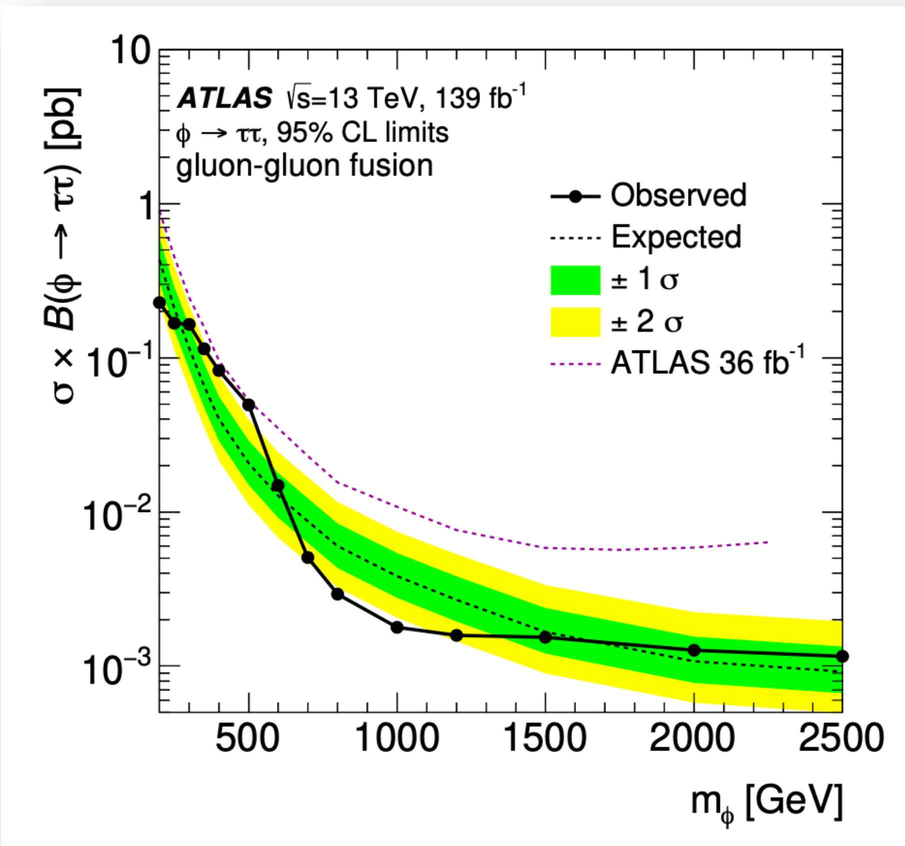
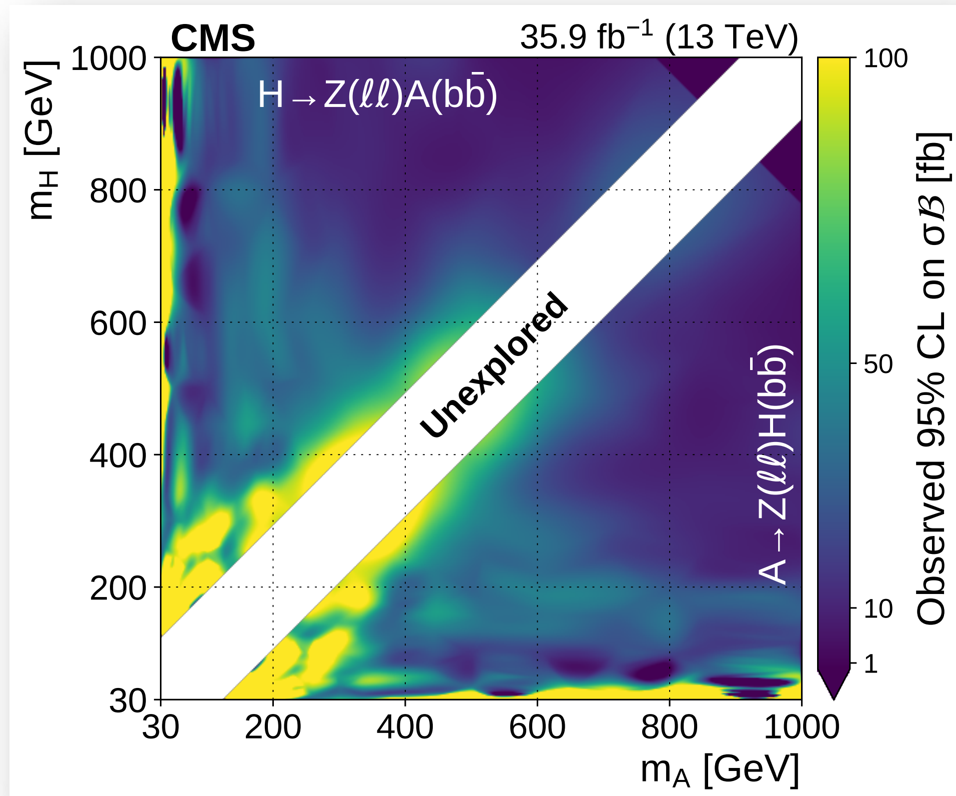
We have come a long way since the discovery of the Higgs boson in 2012:





Searches for additional Higgs bosons (scalars) have come up empty so far:





arXiv:2002.12223

arXiv:1911.03781

Because of the decoupling theorem, these two observations are related:

- A SM-like 125 GeV Higgs
- Absence of new particles at the weak scale

Decoupling theorem:

Effects of heavy new particles on low-energy observables must diminish as the heavy mass tends to infinity.

In the SM, generically, decoupling effect goes like

$$\mathcal{O}\left(\frac{v^2}{M_{\rm new}^2}\right) \sim 5\% \times \left(\frac{1\ \rm TeV}{\Lambda}\right)^2$$

For O(15%) accuracy in HVV couplings, M_{new} >~ 600 GeV!

Question:

If we continue to pursue the precision in the Higgs coupling measurements, is there any value in direct searches for additional, heavy Higgs bosons?

The answer is a resounding "YES!" as the argument for decoupling is not air-tight.

There could be additional heavy Higgs bosons at the weak scale while still having a Standard-Model like 125 GeV Higgs.

It goes by the name of "Alignment without decoupling."

Gunion and Haber, hep-ph/0207010
Delgado, Nardini and Quiros: 1303.0800
Craig, Galloway and Thomas: 1305.2424
Carena, IL, Shah, Wagner: 1310.2248

- First consider the CP-conserving 2HDM:

$$\mathcal{V} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}]$$

$$+\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$

$$+\left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\},$$

- There exists a “basis” where all parameters are real. The VEV’s are

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix},$$

$$v^2 \equiv v_1^2 + v_2^2 = \frac{4m_W^2}{g^2} = (246\ \text{GeV})^2 \qquad \tan\beta = \frac{v_2}{v_1}$$

- There are 8 real degrees of freedom:
  3 eaten Goldstones and 5 physical scalars -- 2 charged Higgs, 1 CP-odd neutral Higgs and 2 CP-even neutral Higgs.

- The mixing angle in the CP-even neutral sector is defined as

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \equiv R(\alpha) \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

- The 2x2 mass matrix can be diagonalized:

$$R^T(\alpha) \begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} R(\alpha) = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix}$$

- To see how “alignment without decoupling” arises, recall that the CP-even scalar couplings to VV are dictated by the respective ”strength” of the VEVs:

$$g_{h_i VV} = \frac{1}{2} g^2 v_i \ , \quad i = 1, 2$$

- It is possible to rotate to a basis where where all the VEV is concentrated in one of the scalars:

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

$$\langle H_1^0 \rangle = v/\sqrt{2} \text{ and } \langle H_2^0 \rangle = 0$$

This is called the Higgs basis and is of singular importance for alignment without decoupling!

- If parameters in the Lagrangian are such that, in the Higgs basis, the scalar mass matrix is diagonal:

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \qquad\qquad \mathcal{M}_{12} \approx 0$$

Then the mass eigenstate that carries the full VEV will be SM-like irrespective of "m_A"!

"Alignment without decoupling" occurs when

Higgs basis = Mass eigenbasis

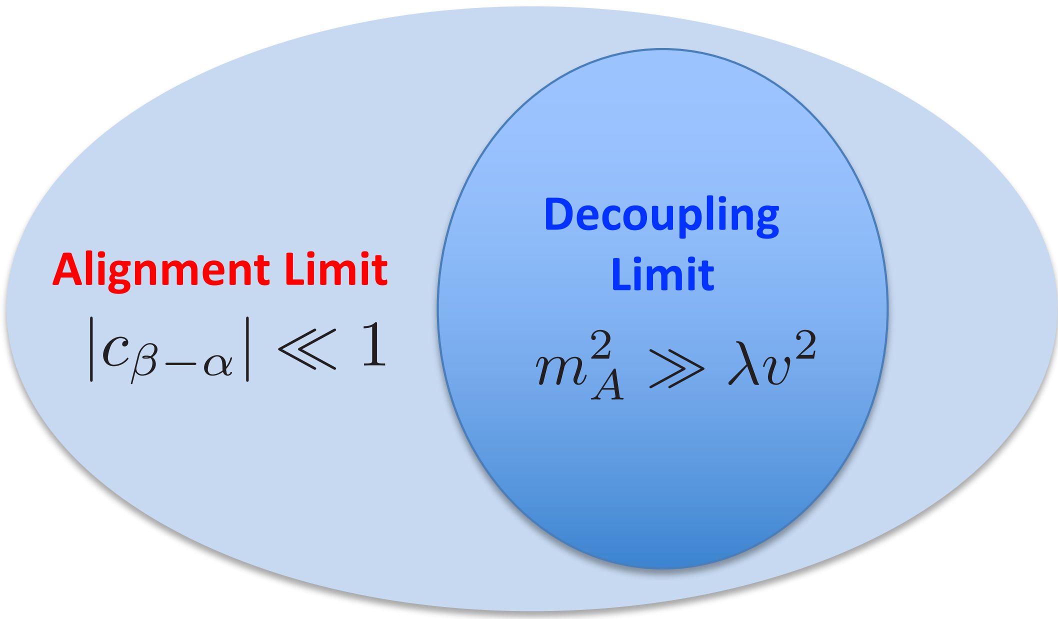
Carena, Haber, IL, Shah, Wagner: 1410.4969

- In the alignment limit

$$g_{hVV} = g_{hVV}^{\mathrm{SM}}\ s_{\beta-\alpha} \qquad\qquad |c_{\beta-\alpha}| \ll 1$$

- The condition is more general than the “decoupling limit”:

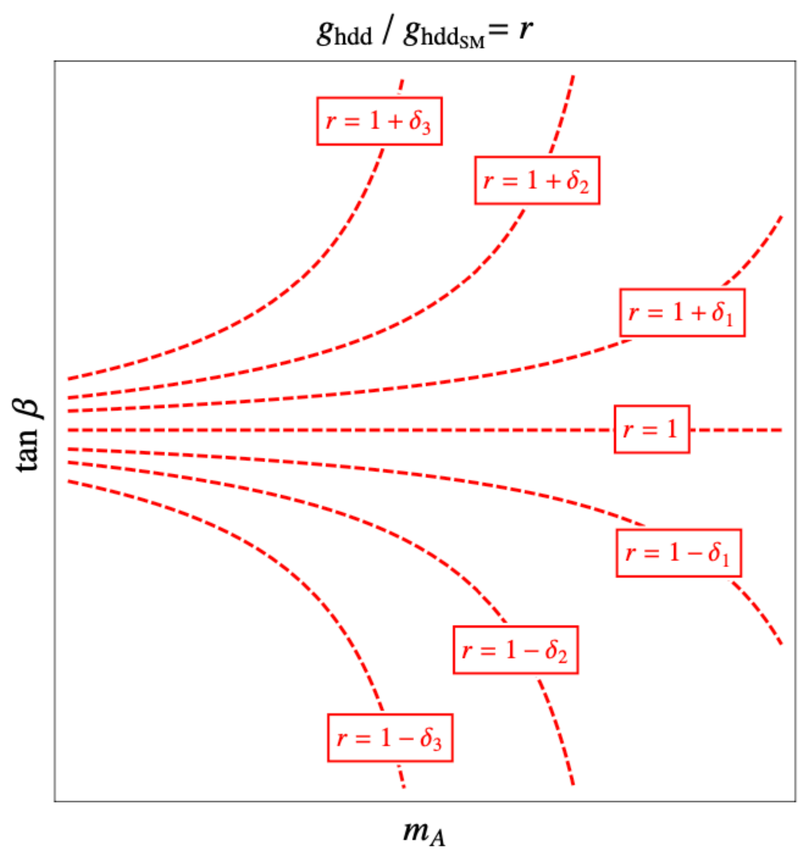
$$m_A^2 \gg \lambda v^2$$



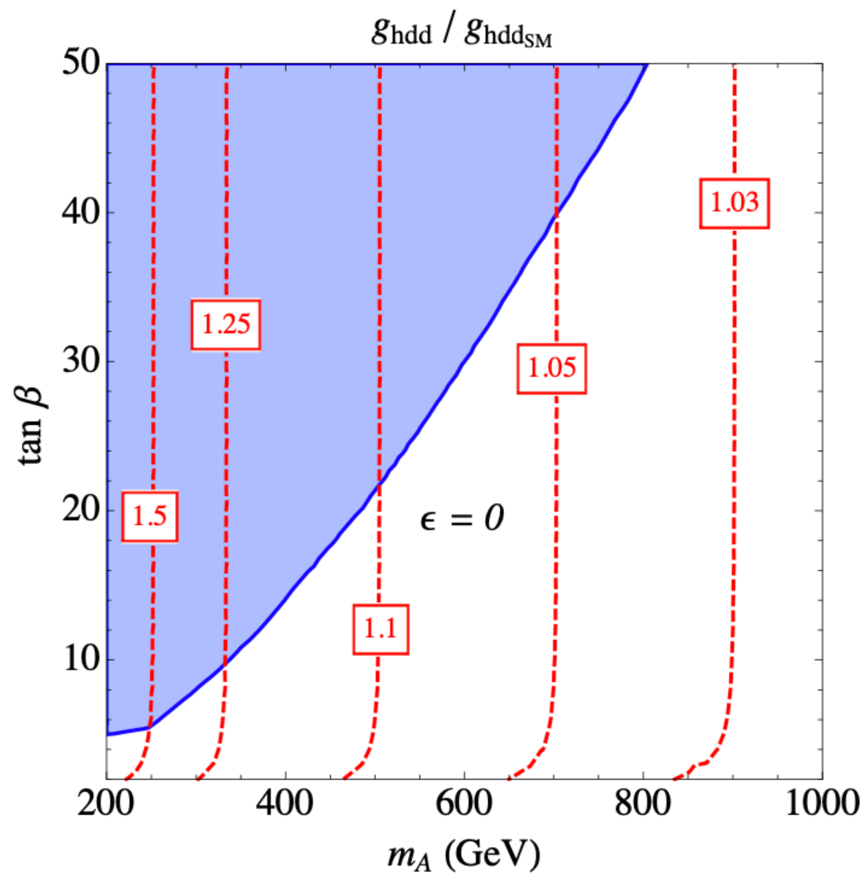
Experimental data point to an “approximate” alignment limit!

- There are essentially two possibilities to introduce fermions in 2HDM. The more popular one is the Type II model (because of SUSY):

$$g_{hdd} = -\frac{s_\alpha}{c_\beta} g_f \qquad g_{huu} = \frac{c_\alpha}{s_\beta} g_f$$



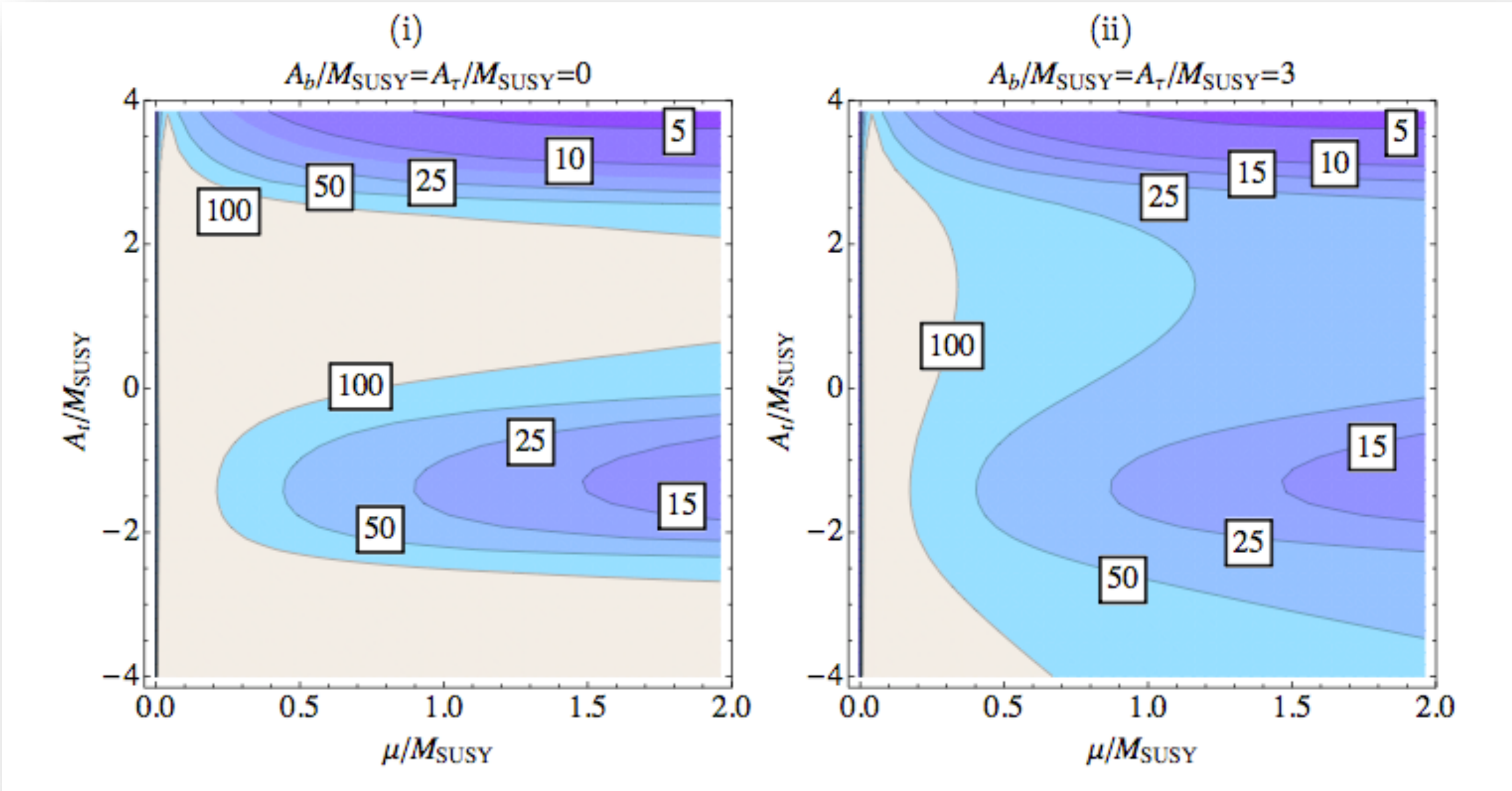
Alignment without decoupling



Decoupling Limit

Alignment without decoupling is more generic than you think:

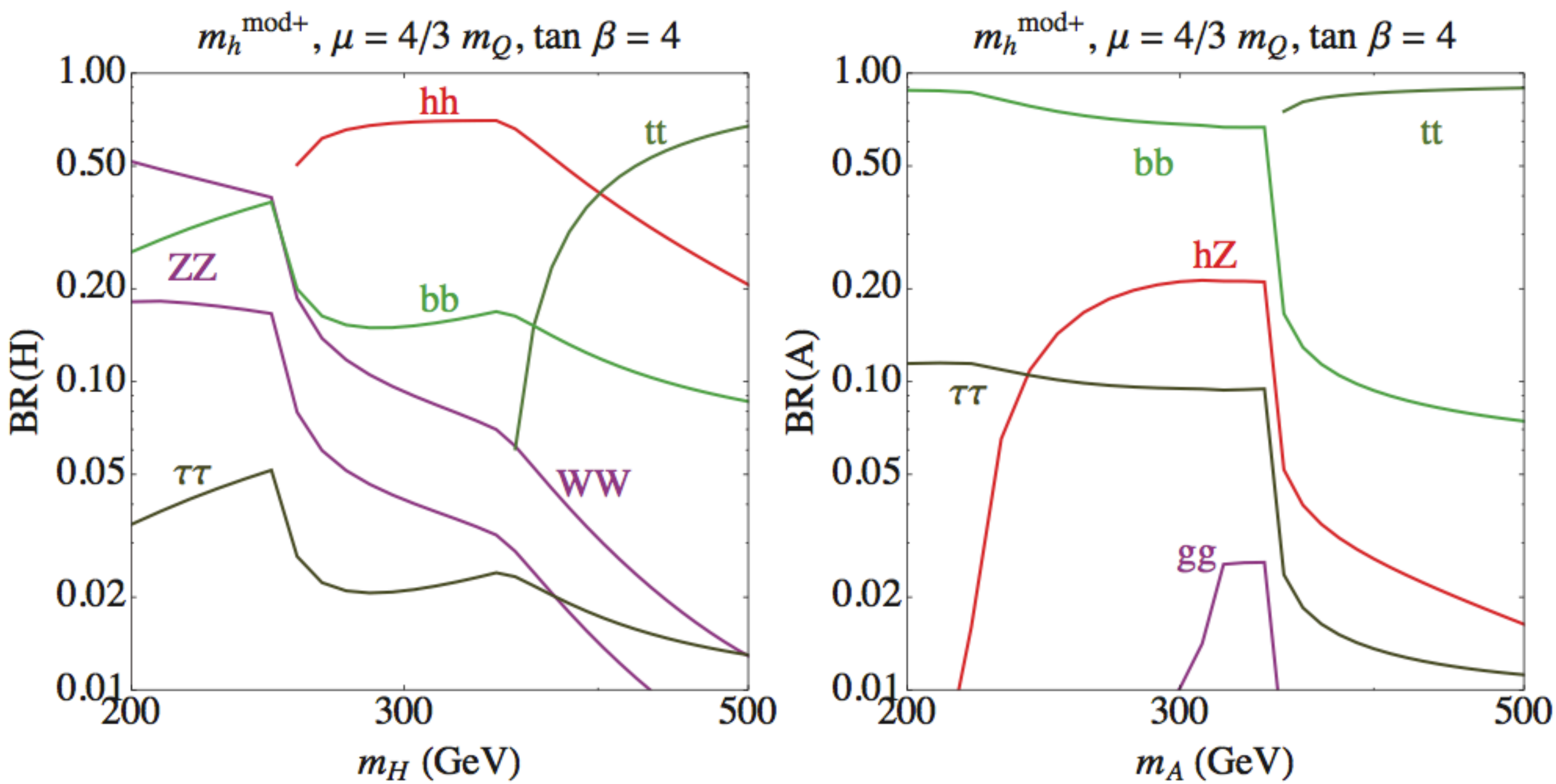
In MSSM it usually happens at moderate tanβ:



In 2HDM and NMSSM, alignment without decoupling usually occurs at low tanβ < 5.

Carena, IL, Shah, Wagner: 1310.2248

Search strategies for additional scalars could be very different from traditional search channels :



Dominant decay channels are WW, hh and tt, which are different from the most considered bb and tau tau!

Carena, Haber, IL, Shah and Wagner: 1410.4969

- The eventual goal is to study the CP-violating 2HDM, but it is instructive to take a look at NMSSM (MSSM + a singlet scalar).

  In the Higgs basis:

$$\langle H_1^0 \rangle = \frac{v}{\sqrt{2}}\,, \qquad \langle H_2^0 \rangle = 0\,, \qquad \langle S \rangle \equiv v_s$$

- The CP-even neutral sector now has 3 scalars:

$$\mathcal{M}_S^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 & \mathcal{M}_{13}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 & \mathcal{M}_{23}^2 \\ \mathcal{M}_{13}^2 & \mathcal{M}_{23}^2 & \mathcal{M}_{33}^2 \end{pmatrix}$$

- Exact alignment ➔ H_1 is a mass eigenstate:

$$\mathcal{M}_{12}^2 = 0\,, \qquad \mathcal{M}_{13}^2 = 0$$

Carena, Haber, IL, Shah and Wagner: 1510.09137

Higgs Alignment in CP-violating 2HDM

- The most general Higgs potential

$$\begin{aligned}\mathcal{V} = {}& m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\ &+ \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.} \right] \ ,\end{aligned}$$

Since we allow for the possibility of CPX, the following parameters could be complex:

$$\{ m_{12}^2, \lambda_5, \lambda_6, \lambda_7 \}$$

- Assuming the vacuum preserves $U(1)_{em}$:

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} , \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2\, e^{i\xi} \end{pmatrix}$$

A potential phase in $< \Phi_1 >$ is removed by the global hypercharge rotation.

- Minimization of the potential relates some of the parameters:

$$\begin{aligned} m_{11}^2 &= \mathrm{Re}(m_{12}^2 e^{i\xi}) \tan\beta - \frac{1}{2} v^2 \left[\lambda_1 c_\beta^2 + \lambda_{345} s_\beta^2 + 3\,\mathrm{Re}(\lambda_6 e^{i\xi}) s_\beta c_\beta + \mathrm{Re}(\lambda_7 e^{i\xi}) s_\beta^2 \tan\beta \right] \\ m_{22}^2 &= \mathrm{Re}(m_{12}^2 e^{i\xi}) \cot\beta - \frac{1}{2} v^2 \left[\lambda_2 s_\beta^2 + \lambda_{345} c_\beta^2 + \mathrm{Re}(\lambda_6 e^{i\xi}) c_\beta^2 \cot\beta + 3\,\mathrm{Re}(\lambda_7 e^{i\xi}) s_\beta c_\beta \right] \\ \mathrm{Im}(m_{12}^2 e^{i\xi}) &= \frac{1}{2} v^2 \left[\mathrm{Im}(\lambda_5 e^{2i\xi}) s_\beta c_\beta + \mathrm{Im}(\lambda_6 e^{i\xi}) c_\beta^2 + \mathrm{Im}(\lambda_7 e^{i\xi}) s_\beta^2 \right] \end{aligned}$$

- Recall the definition of the Higgs basis

$$\langle H_1^0 \rangle = \frac{v}{\sqrt{2}} \,, \qquad \langle H_2^0 \rangle = 0$$

- Rotating H_2 by an arbitrary phase leaves the defining relation of Higgs basis invariant. Two different Higgs bases given by

$$H_1' = H_1 \,, \qquad H_2' = e^{i(\eta' - \eta)} H_2$$

are physically equivalent "Higgs bases."

Higgs basis is really a family of bases labelled by η.

- We can further ”gauge fix” the residual redundancy by writing the potential as follows:

$$\mathcal{V} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left[Y_3 e^{-i\eta} H_1^\dagger H_2 + \text{h.c.}\right]$$
$$+ \frac{Z_1}{2}(H_1^\dagger H_1)^2 + \frac{Z_2}{2}(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \left[\frac{Z_5}{2} e^{-2i\eta}(H_1^\dagger H_2)^2 + Z_6 e^{-i\eta}(H_1^\dagger H_1)(H_1^\dagger H_2) + Z_7 e^{-i\eta}(H_2^\dagger H_2)(H_1^\dagger H_2) + \text{h.c.}\right]$$

2001.01430

Different choices of parameters now truly represent physically distinct theories!

- Potentially complex parameters are

$$\{Y_3, Z_5, Z_6, Z_7\}$$

- Minimization condition in the Higgs basis:

$$Y_1 = -\frac{1}{2} Z_1 v^2 \, , \qquad Y_3 = -\frac{1}{2} Z_6 v^2$$

The first condition is the definition of “v” in the Higgs basis.

The second condition eliminates one complex parameters. So only three are remaining:

$$\{Z_5, Z_6, Z_7\}$$

- If there exists a choice of η such that all three are real, CP is conserved:

$$\mathrm{Im}(Z_5^* Z_6^2) = \mathrm{Im}(Z_5^* Z_7^2) = \mathrm{Im}(Z_6^* Z_7) = 0$$

Lavoura and Silva, hep-ph/9404276

The importance of Z_2 :

- The most general Yukawa interaction in 2HDM introduce tree-level flavor-changing neutral currents (FCNCs) and is severely constrained by data.

- The tree-level FCNCs can be removed by imposing a Z_2 symmetry such that

$$\Phi_1 \to \Phi_1 , \qquad \Phi_2 \to -\Phi_2$$

- The following terms in the scalar potential violates the Z_2 symmetry:

$$m_{12}^2 = \lambda_6 = \lambda_7 = 0$$

- But this is too stringent. For the purpose of removing FCNCs, Z_2 can be broken "softly" by mass terms. In the end we only need

$$\lambda_6 = \lambda_7 = 0 , \qquad m_{12}^2 \neq 0$$

- The Yukawa interaction

$$-\mathcal{L}_Y = \sum_{i=1,2} \left(\bar{\mathrm{u}}_L\, \Phi_i^{0\,*}\, \mathcal{Y}_i^{\mathrm{u}}\, \mathrm{u}_R - \bar{\mathrm{d}}_L\, \mathcal{K}^\dagger\, \Phi_i^-\, \mathcal{Y}_i^{\mathrm{u}}\, \mathrm{u}_R + \bar{\mathrm{u}}_L\, \mathcal{K}\, \Phi_i^+\, \mathcal{Y}_i^{\mathrm{d}\,\dagger}\, \mathrm{d}_R + \bar{\mathrm{d}}_L\, \Phi_i^0\, \mathcal{Y}_i^{\mathrm{d}\,\dagger}\, \mathrm{d}_R + \mathrm{h.c.} \right)$$

must also respect the Z_2 symmetry, leading to two possibilities:

$$\text{Type I}: \qquad \mathcal{Y}_i^{\mathrm{u}} = \mathcal{Y}_i^{\mathrm{d}} = 0\ ,$$

$$\text{Type II}: \qquad \mathcal{Y}_j^{\mathrm{u}} = \mathcal{Y}_i^{\mathrm{d}} = 0\ ,\ i \neq j$$

- In the literature the 2HDM Lagrangian is commonly presented in a "basis" where the Z_2 symmetry is manifest. This is called "Z_2 basis."

- The complex 2HDM (C2HDM):

  A general 2HDM with a softly broken Z_2 symmetry, defined in a basis where λ_6 = λ_7=0 and the VEVs are real and non-negative, $\xi = 0$. (This can be achieved by rephasing Φ_2 .)

- There are a total of 9 parameters in C2HDM:

$$\{v, \tan\beta, \mathrm{Re}\, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \mathrm{Re}\,\lambda_5, \mathrm{Im}\,\lambda_5\}$$

- In the Higgs basis the softly broken Z_2 is not manifest and appears as the following constraint on the parameters:

$$(Z_1 - Z_2)\big[Z_{34}Z_{67}^* - Z_1Z_7^* - Z_2Z_6^* + Z_5^*Z_{67})\big] - 2Z_{67}^*\big(|Z_6|^2 - |Z_7|^2\big) = 0\,.$$

2001.01430

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- In the end we choose

$$\{v, m_{h_1}, m_{h_2}, m_{h_3}, m_{H^\pm}, \theta_{12}, \theta_{13}, Z_3, \mathrm{Re}[\tilde{Z}_7]\}$$

Alignment without decoupling in C2HDM

- In the neutral scalar sector, there are 3 physical scalars which can mix. So the mass matrix is 3x3:

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + \phi_1^0 + iG^0\right) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(\phi_2^0 + ia^0\right) \end{pmatrix}$$

$$R\,\mathcal{M}^2\,R^T = \mathcal{M}_D^2 \equiv \mathrm{diag}\;(m_1^2, m_2^2, m_3^2)$$

- We can parameterize the rotation matrix *R* by three ”Euler angles:”

$$R = R_{12}R_{13}\overline{R}_{23} = \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & -s_{13} \\ 0 & 1 & 0 \\ s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \bar{c}_{23} & -\bar{s}_{23} \\ 0 & \bar{s}_{23} & \bar{c}_{23} \end{pmatrix}$$

But $\bar{\theta}_{23}$ simply rotates ϕ_2^0 and a^0, which corresponds to

$$H_2 \to e^{i\bar{\theta}_{23}} H_2$$

So it can be re-absorbed into

$$\theta_{23} \equiv \bar{\theta}_{23} + \eta$$

In the end, one can diagonalize the mass matrix using just two angles.

2001.01430

- This consideration motivates absorbing R_{23} into the mass matrix itself:

$$\widetilde{\mathcal{M}}^2 \equiv \overline{R}_{23}\, \mathcal{M}^2\, \overline{R}_{23}^T$$

$$\widetilde{R}\, \widetilde{\mathcal{M}}^2\, \widetilde{R}^T = \mathrm{diag}\ \left(m_1^2, m_2^2, m_3^2\right)\ , \qquad \widetilde{R} = R_{12}R_{13} = \begin{pmatrix} c_{12}c_{13} & -s_{12} & -c_{12}s_{13} \\ s_{12}c_{13} & c_{12} & -s_{12}s_{13} \\ s_{13} & 0 & c_{13} \end{pmatrix}$$

- The exact alignment limit is given by

$$\widetilde{\mathcal{M}}^2_{12} = \widetilde{\mathcal{M}}^2_{13} = 0$$

When this occurs, there is a mass eigenstate which carries the full strength of the VEV and will be SM-like.

The explicit expression:

$$\widetilde{\mathcal{M}}^2 \equiv \overline{R}_{23}\,\mathcal{M}^2\,\overline{R}_{23}^T$$
$$= v^2 \begin{pmatrix} Z_1 & \mathrm{Re}[\tilde{Z}_6] & -\mathrm{Im}[\tilde{Z}_6] \\ \mathrm{Re}[\tilde{Z}_6] & \mathrm{Re}[\tilde{Z}_5] + A^2/v^2 & -\frac{1}{2}\mathrm{Im}[\tilde{Z}_5] \\ -\mathrm{Im}[\tilde{Z}_6] & -\frac{1}{2}\mathrm{Im}[\tilde{Z}_5] & A^2/v^2 \end{pmatrix}$$

$$\tilde{Z}_5 = Z_5 e^{-2i\theta_{23}},\ \tilde{Z}_{6/7} = Z_{6/7} e^{-i\theta_{23}},\ \theta_{23} = \eta + \bar{\theta}_{23}$$

Alignment conditions:

$$\mathrm{Re}[\tilde{Z}_6] = \mathrm{Im}[\tilde{Z}_6] = 0$$

Mass eigenstates:

$$\begin{pmatrix} h_3 \\ h_2 \\ h_1 \end{pmatrix} = \widetilde{R} \begin{pmatrix} \phi_1^0 \\ \tilde{\phi}_2^0 \\ \tilde{\phi}_3^0 \end{pmatrix} = \widetilde{R} \begin{pmatrix} \phi_1^0 \\ c_{23}\,\phi_2^0 - s_{23}\,a^0 \\ s_{23}\,\phi_2^0 + c_{23}\,a^0 \end{pmatrix}$$

$$m_{h_1} \leq m_{h_2} \leq m_{h_3} \qquad m_{h_1} = 125\ \mathrm{GeV}$$

We are interested in the interplay between the Higgs alignment and CPX in C2HDM. There are two important experimental observations:

- The 125 GeV Higgs is SM-*like*.
- EDM places stringent constraints on CPX.

These motivates considering the *small departures* from

- The exact alignment limit
- The exact CP-conserving limit.

Low, Shah and Wang:2012.00773

Two CP-conserving limits:

- The CP-conserving conditions

$$\mathrm{Im}(Z_5^* Z_6^2) = \mathrm{Im}(Z_5^* Z_7^2) = \mathrm{Im}(Z_6^* Z_7) = 0$$

give rise to two CP-conserving limits:

$$\mathrm{CPC1}: \quad \mathrm{Im}[\tilde{Z}_5] = \mathrm{Im}[\tilde{Z}_6] = \mathrm{Im}[\tilde{Z}_7] = 0$$
$$\mathrm{CPC2}: \quad \mathrm{Im}[\tilde{Z}_5] = \mathrm{Re}[\tilde{Z}_6] = \mathrm{Re}[\tilde{Z}_7] = 0$$

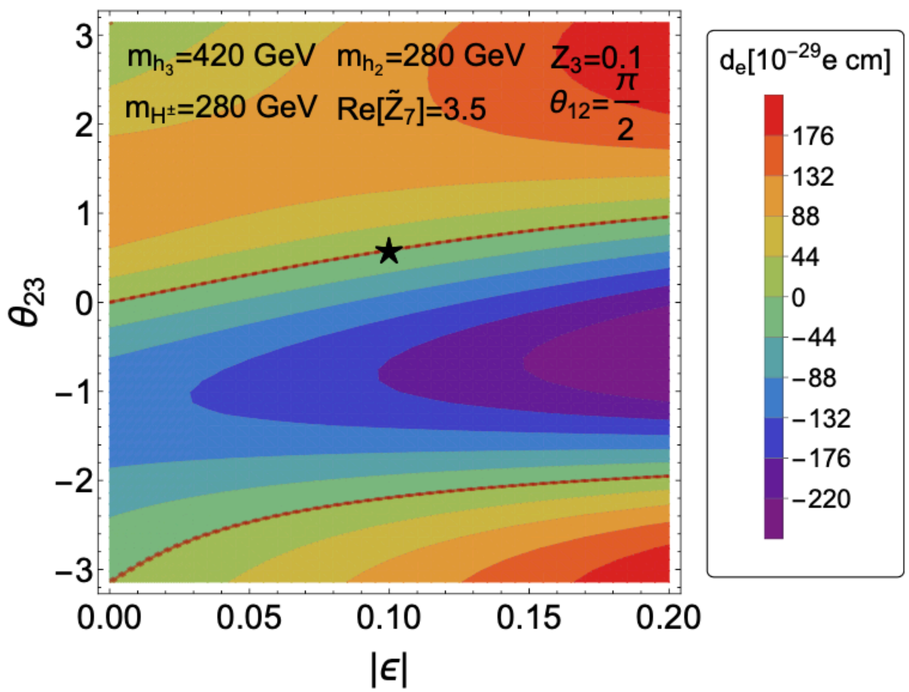
- In the CP-limit, there are two CP-even scalars (SM-like Higgs and H) and one CP-odd scalar (A). Only the two CP-even scalars could mix.

- In small departure from the CP-limit, each mass eigenstate retains its dominant “CP-character,” with small mixtures with other scalars.

- In CPC1, the SM-like Higgs has a small mixture with the CP-odd component in H_2. In this case the small CPV implies small departures from the alignment limit. EDM gives

$$\epsilon \sim \mathcal{O}(10^{-4})$$

- In CPC 2, the SM-like Higgs has a small mixture with the CP-even component in H_2. In this case the CP-limit is independent of the alignment limit!



<u>Collider phenomenology</u>

The benchmark:

$$\{Z_3, \mathrm{Re}[\tilde{Z}_7], \theta_{12}, \theta_{23}, \epsilon\} = \{0.1, 3.5, \pi/2, 0.59, -0.1\},$$
$$\{m_{h_3}, m_{h_2}, m_{H^\pm}\} = \{420, 280, 280\}\ \mathrm{GeV}\ . \quad (21)$$

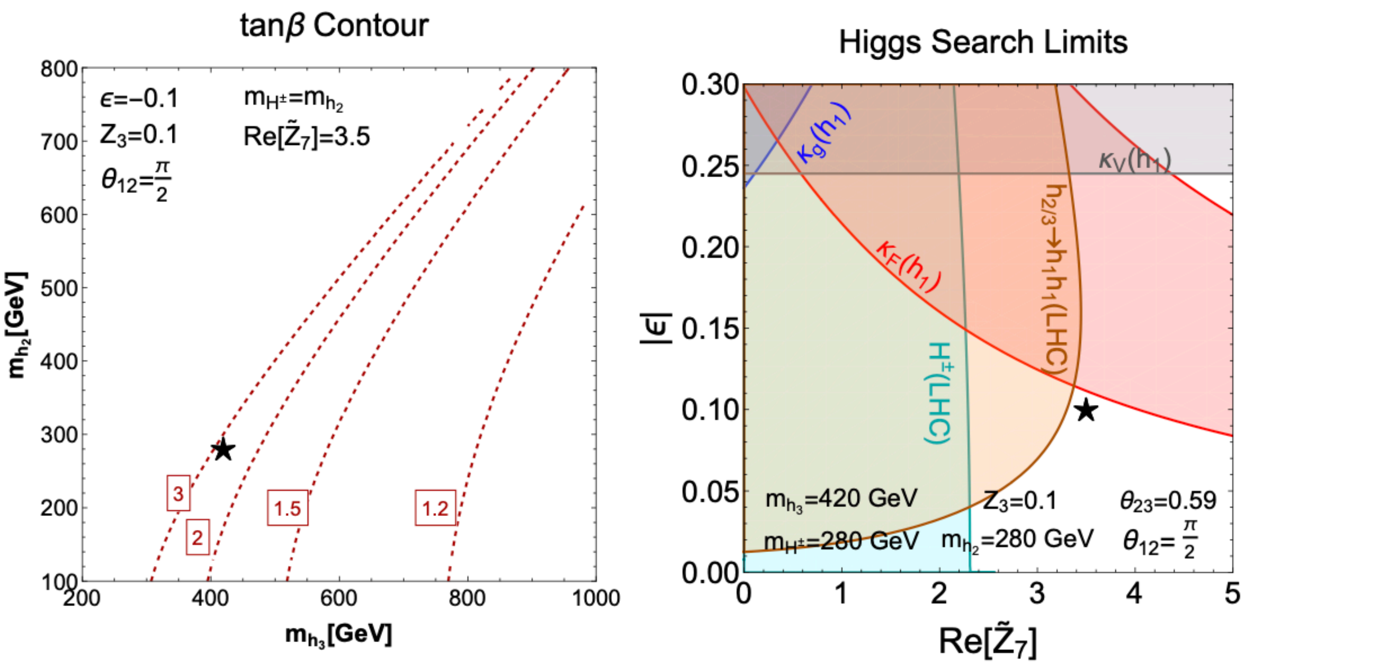


FIG. 1: *Left:* $\tan\beta$ contours in the m_{h_2} - m_{h_3} plane. *Right:* LHC constraints on $|\epsilon|$ from Higgs couplings with gluons (κ_g), vector bosons (κ_V), fermions (κ_F) and photons (κ_γ), as well as searches for $H^+ \to tb$ (cyan) and $h_{2/3} \to h_1 h_1$ (orange) . Stars denote our benchmark point.

- Heavy Higgs decays

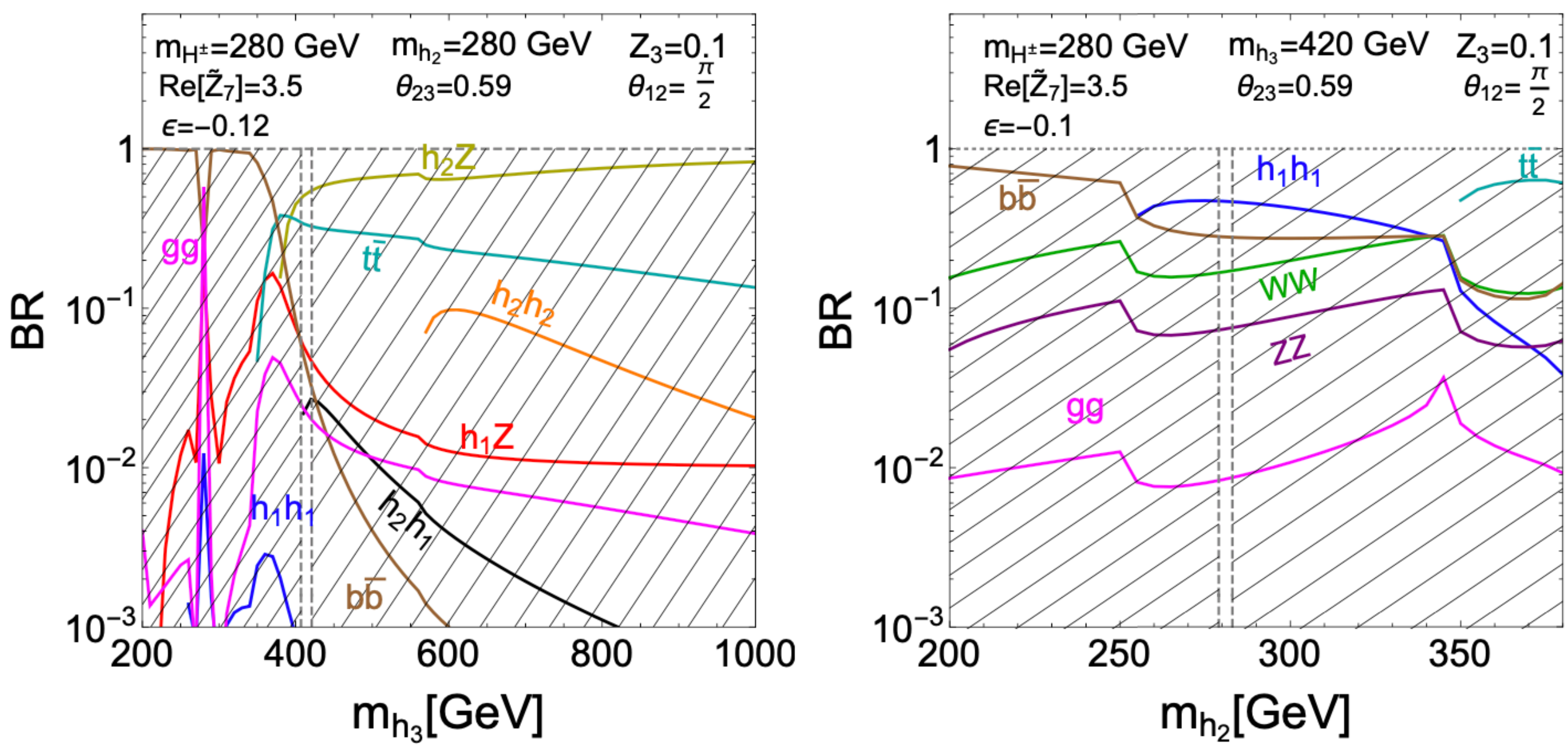


FIG. 3: Branching ratios for h_3 (left) and h_2 (right) for the listed parameters. Grey dashed lines denote mass spectra in tension with eEDM constraints for chosen set of parameters.

- The most interesting pattern is the Higgs-to-Higgs decay:

$$h_3 \to h_2 h_1$$

- This decay is CP-violating and vanishes in the exact alignment limit:

$$g_{h_1 h_2 h_3} = \epsilon\, v\; \mathrm{Re}[\tilde{Z}_7 e^{-2i\theta_{12}}]$$

The mere existence of this decay is indicative of CPV!

- Final state with three 125 GeV Higgs bosons is very distinct, and has not been searched for at the LHC!

$$\sigma(gg \to h_2) \simeq 3.2 \text{ pb} , \qquad \sigma(gg \to h_3) \simeq 1.7 \text{ pb}$$

- At the High Luminosity LHC with 3000 /fb, the CP-violating triple Higgs event could have a large rate:

$$N(h_3 \to h_2 h_1 \to h_1 h_1 h_1) = 7 \times 10^4$$

Now is a good time to start an experimental program on triple Higgs final states!

Conclusion:

- There is an interesting interplay between alignment limit and CP-conserving limit in C2HDM. In one case, the alignment limit is identical with the CP-limit, while in the other case they are independent.

- There is a smoking-gun signal for CP violation at the LHC in C2HDM, without recourse to angular distributions, by searching for CP-violating triple Higgs bosons!