Higgs Alignment and CP Violation in 2HDM

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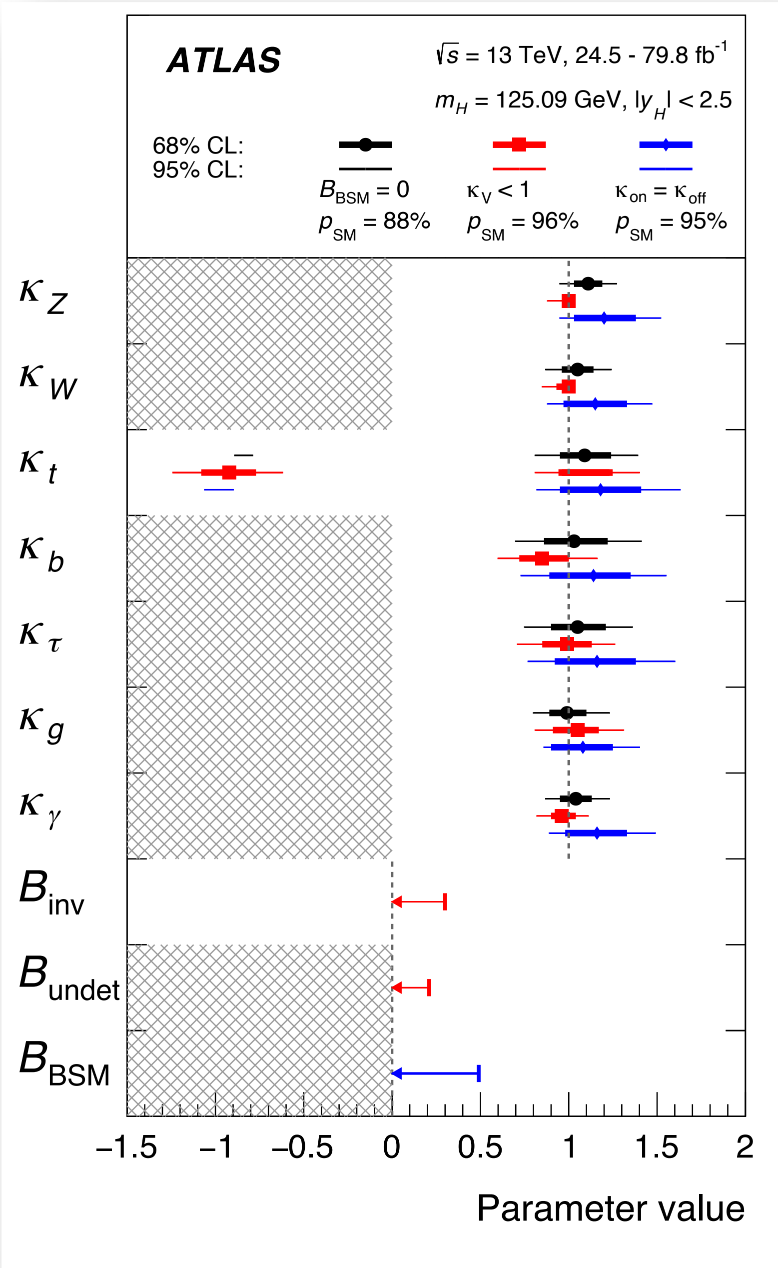
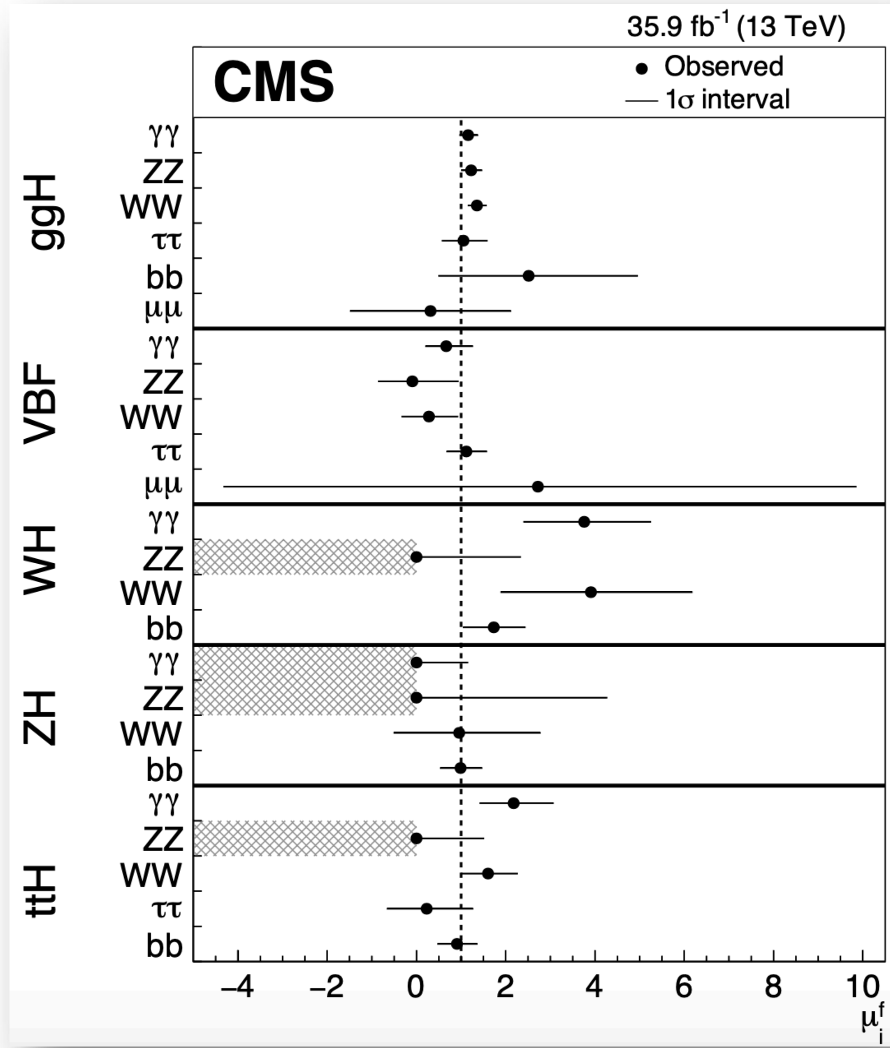
December 9, 2020

NCTS ANNUAL THEORY MEETING 2020
Particles, Cosmology and Strings
December 9-11
Lecture Room A of NCTS
4F, 3rd General Building, NTHU

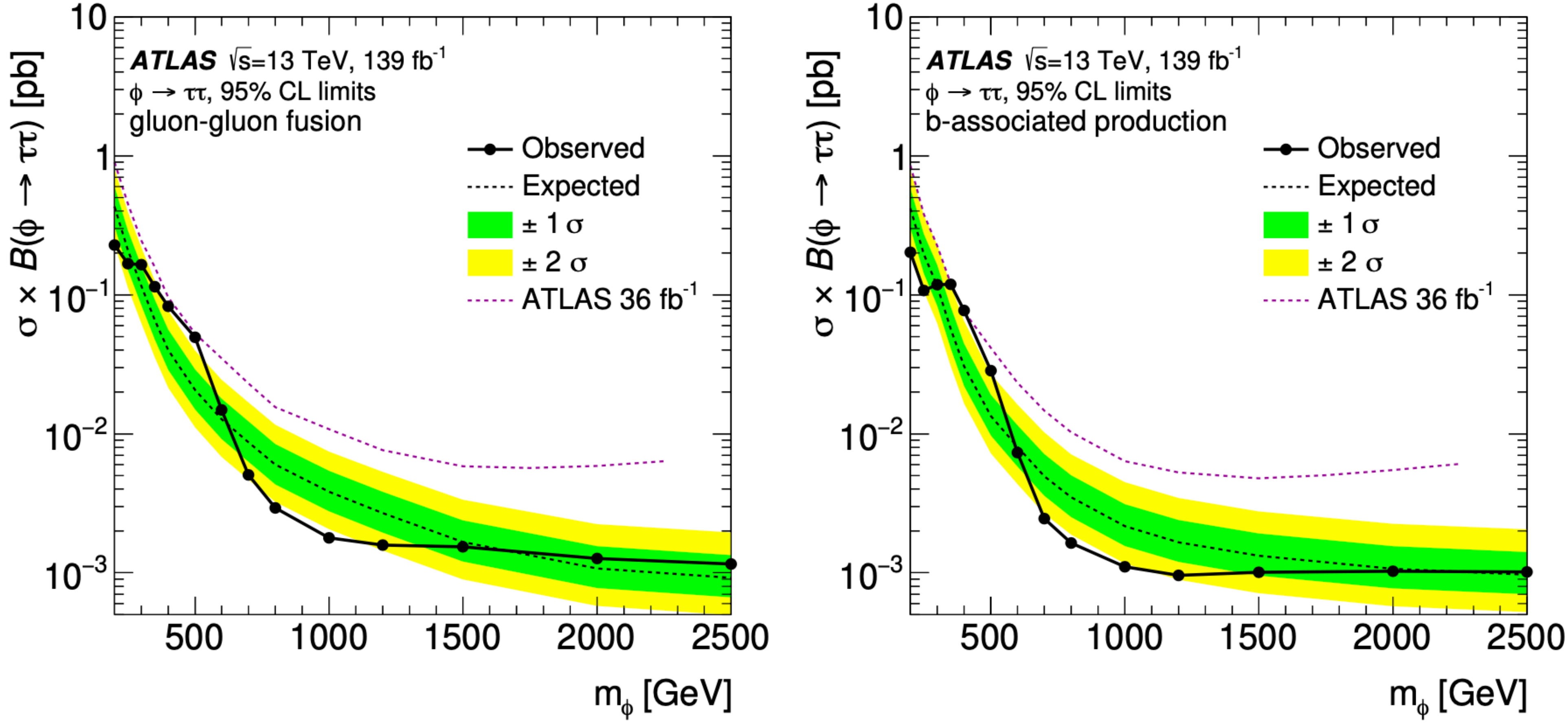
國立清華大學
NATIONAL TSING HUA UNIVERSITY

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

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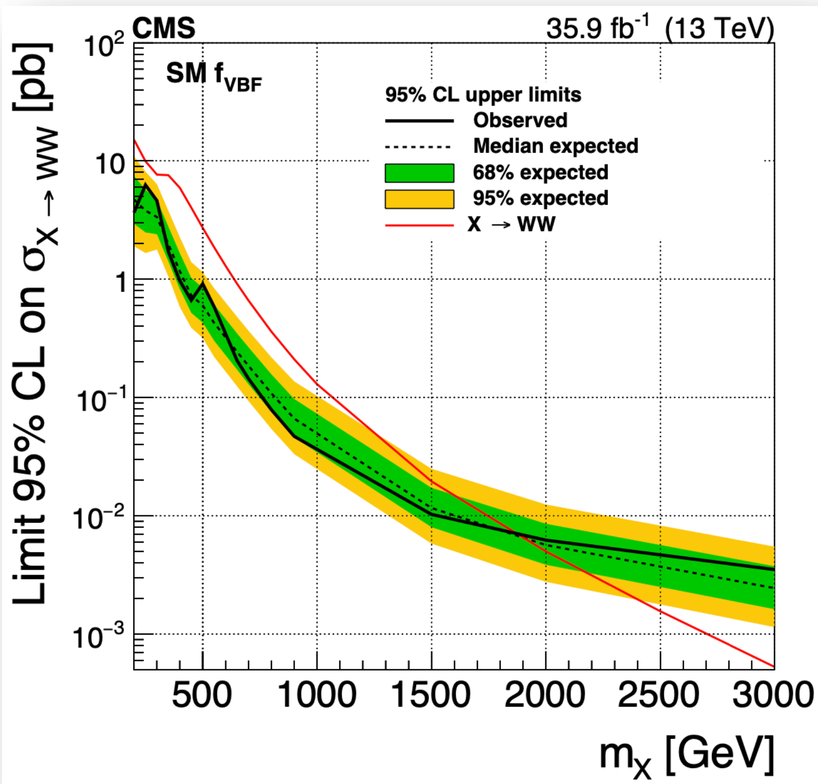

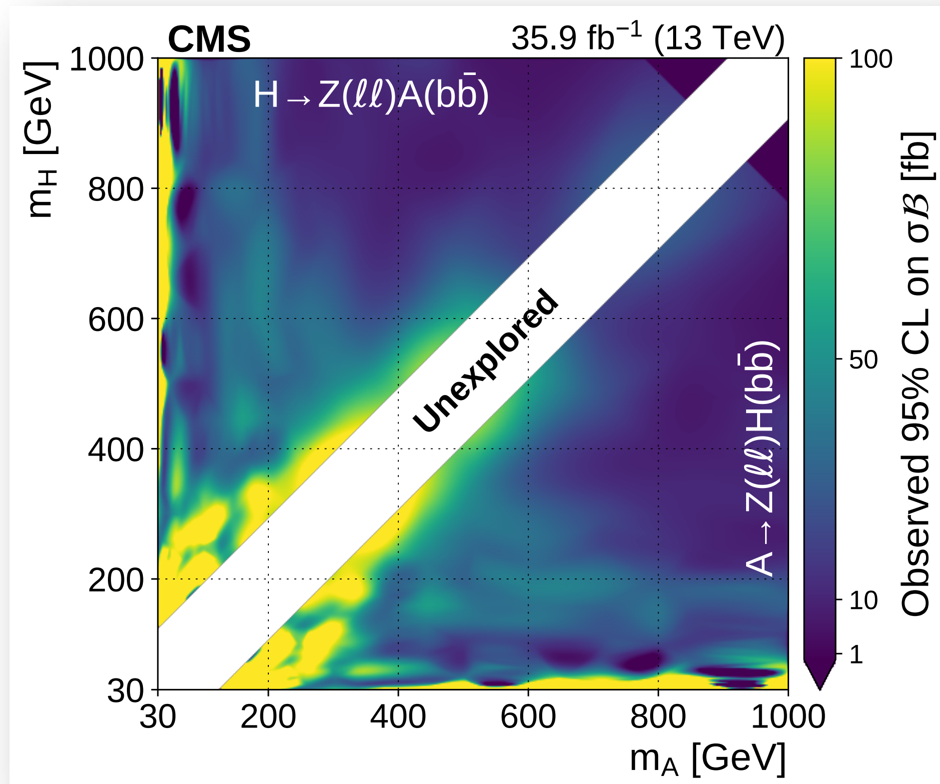

arXiv:1912.01594

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.

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Decoupling theorem:

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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?

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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.”

In fact, it was pointed out almost 20 years ago that, in the 2HDM there could be a SM-like Higgs without "heavy" non-SM scalars:

Gunion and Haber, hep-ph/0207010

V. A SM-LIKE HIGGS BOSON WITHOUT DECOUPLING

We have demonstrated above that the decoupling limit (where $m_A^2 \gg |\lambda_i| v^2$) implies that $|c_{\beta-\alpha}| \ll 1$. However, the $|c_{\beta-\alpha}| \ll 1$ limit is more general than the decoupling limit. From eq. (36), one learns that $|c_{\beta-\alpha}| \ll 1$ implies that either (i) $m_A^2 \gg \lambda_A v^2$, and/or (ii) $|\widehat{\lambda}| \ll 1$ subject to the condition specified by eq. (33). Case (i) is the decoupling limit described in

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"Alignment without decoupling" was (re)discovered by two groups:

- MSSM augmented by a triplet scalar in 1303.0800 by Delgado, Nardini and Quiros.
- Studies on the parameter space of general THDMs by Craig, Galloway and Thomas in 1305.2424.

- 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

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

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

- The particle spectrum contains 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:

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

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- 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:

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

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

Carena, Haber, IL, Shah, Wagner: 1410.4969

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"Alignment without decoupling" occurs when

Higgs basis = Mass eigenbasis

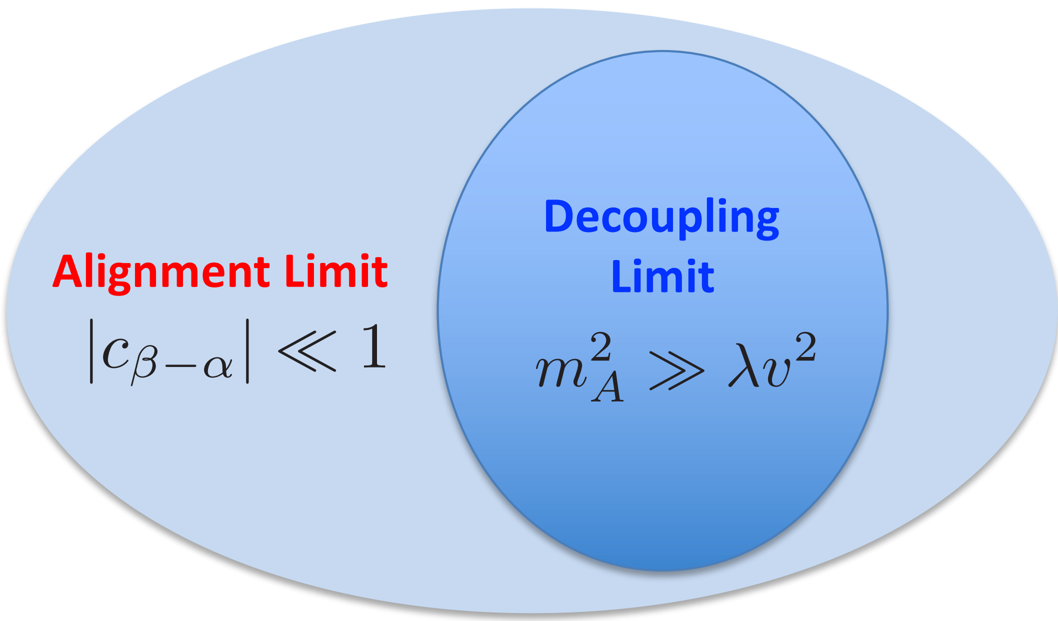
Carena, Haber, IL, Shah, Wagner: 1410.4969

- In the alignment limit

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

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

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



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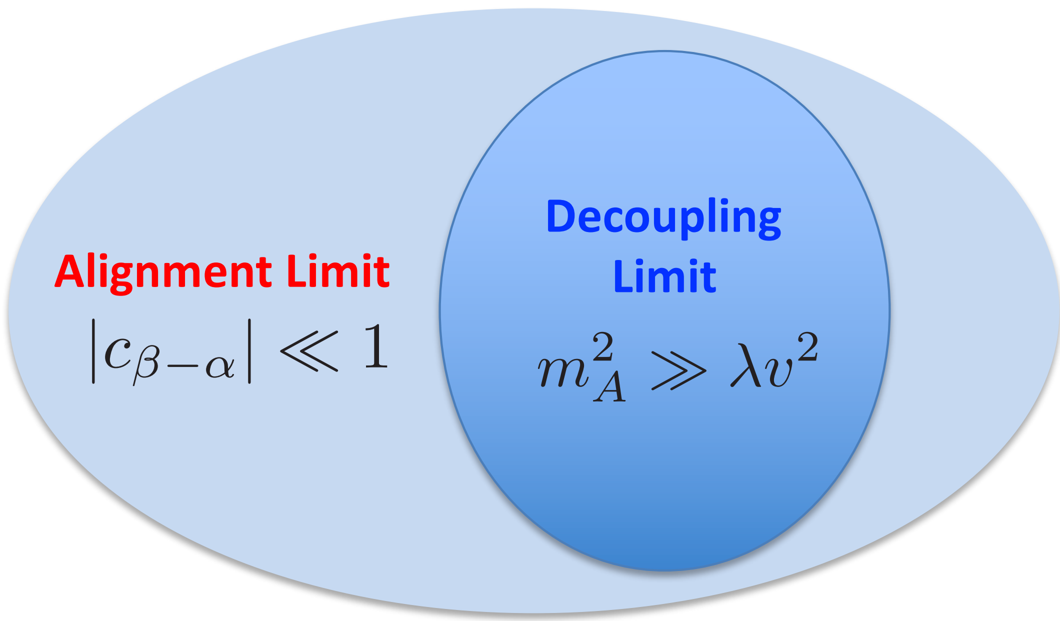
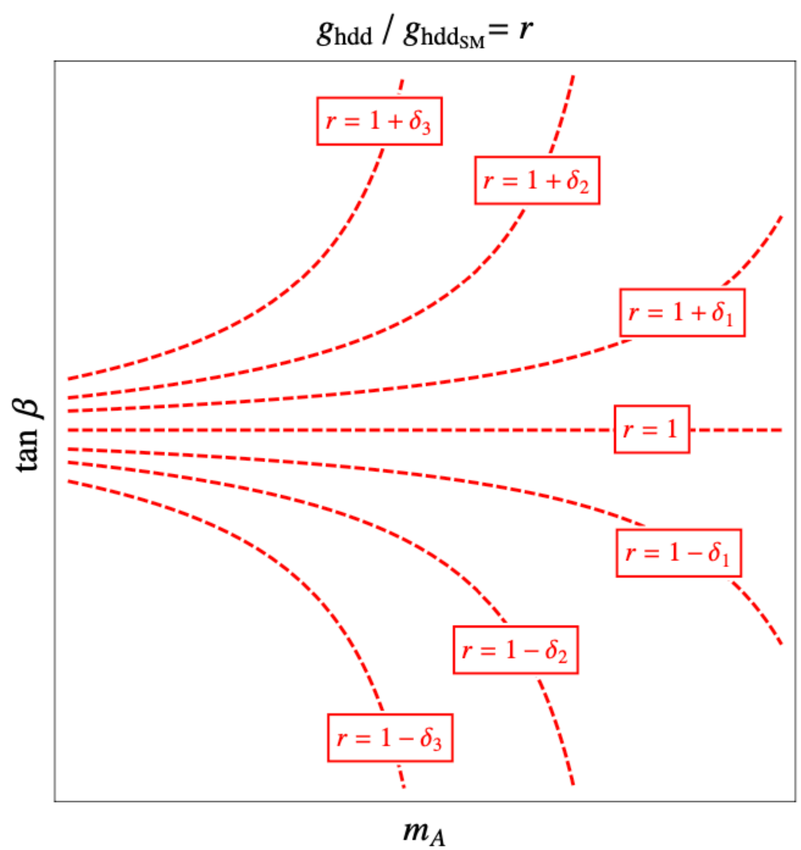


Experimental data point to an "approximate" alignment limit!

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

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



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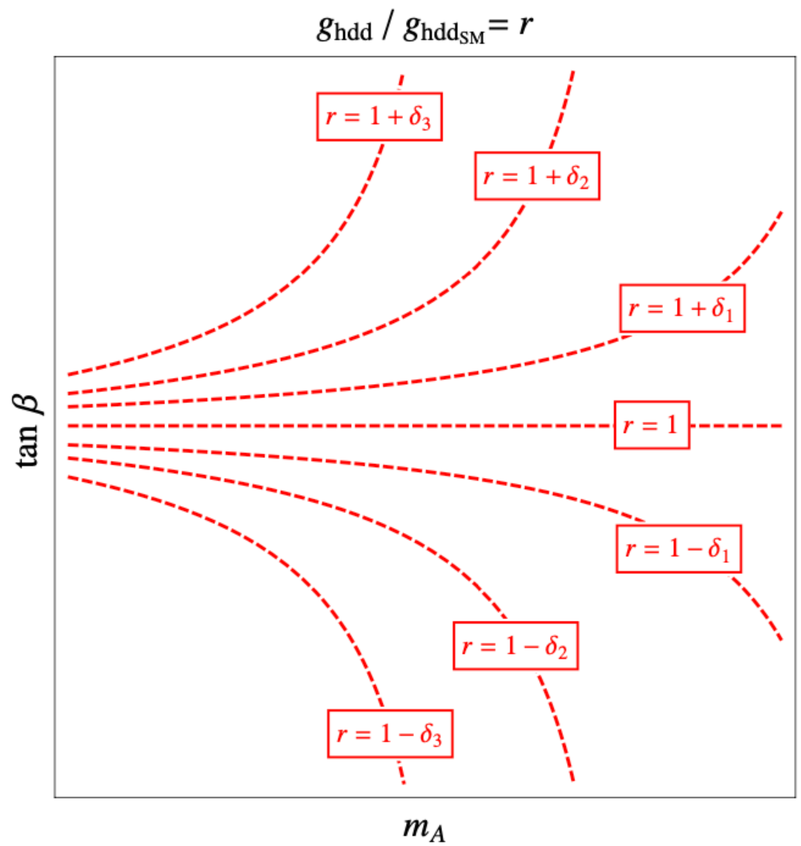
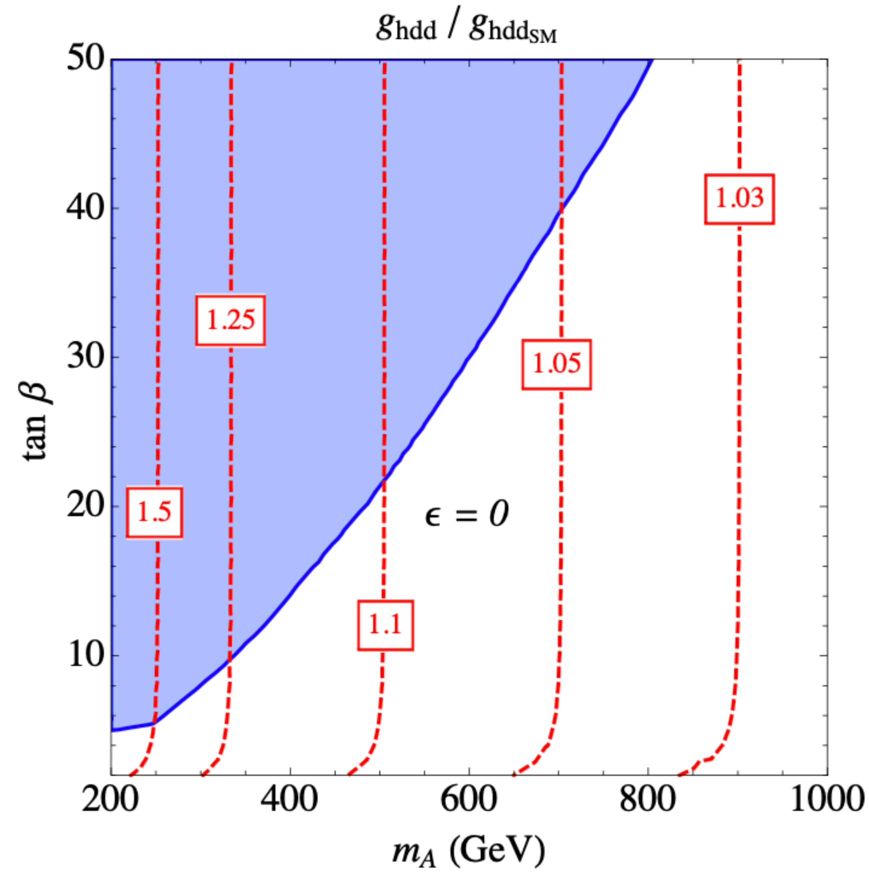


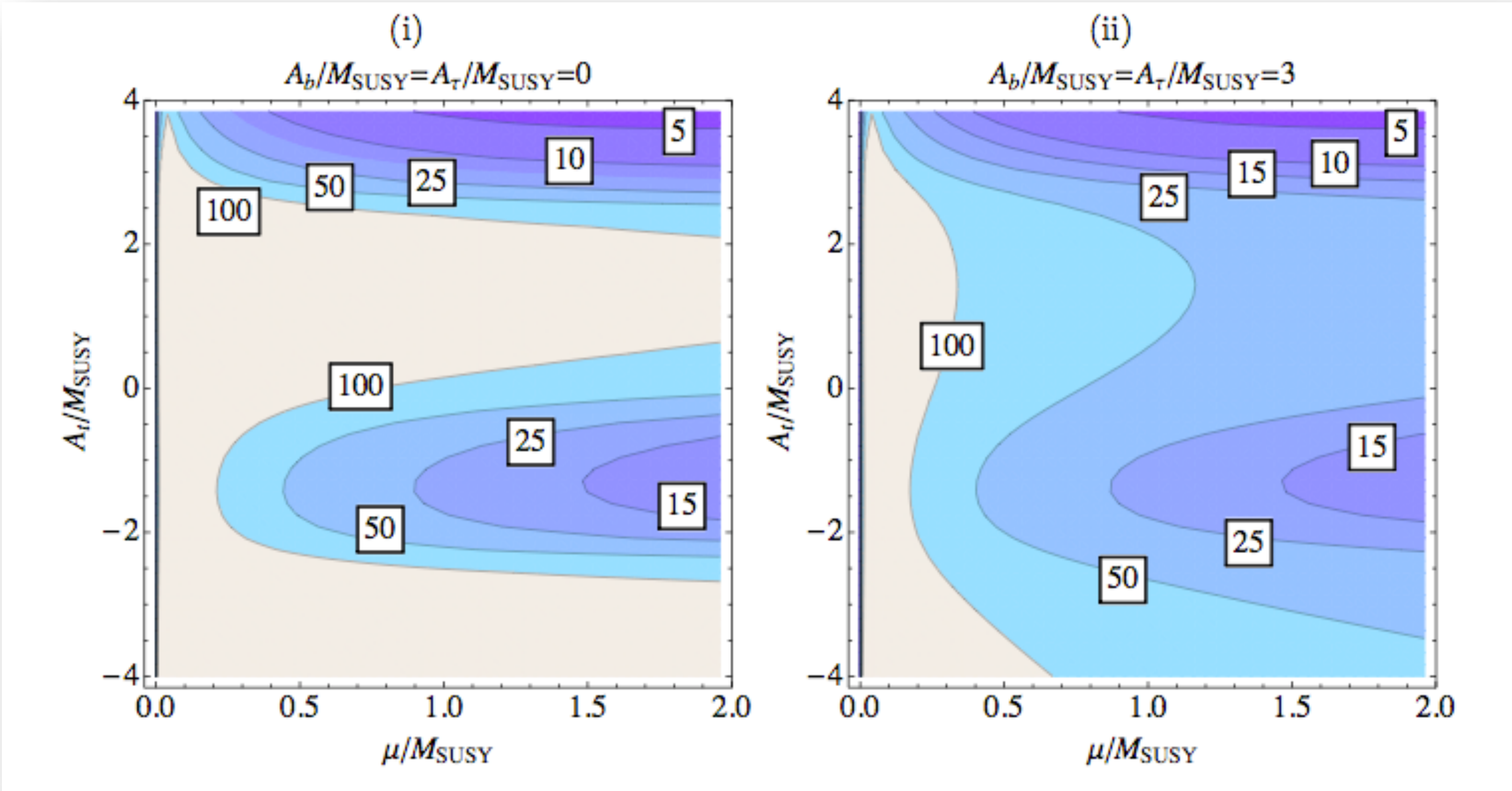


Alignment without decoupling

Decoupling Limit

Alignment without decoupling is more generic than you think:

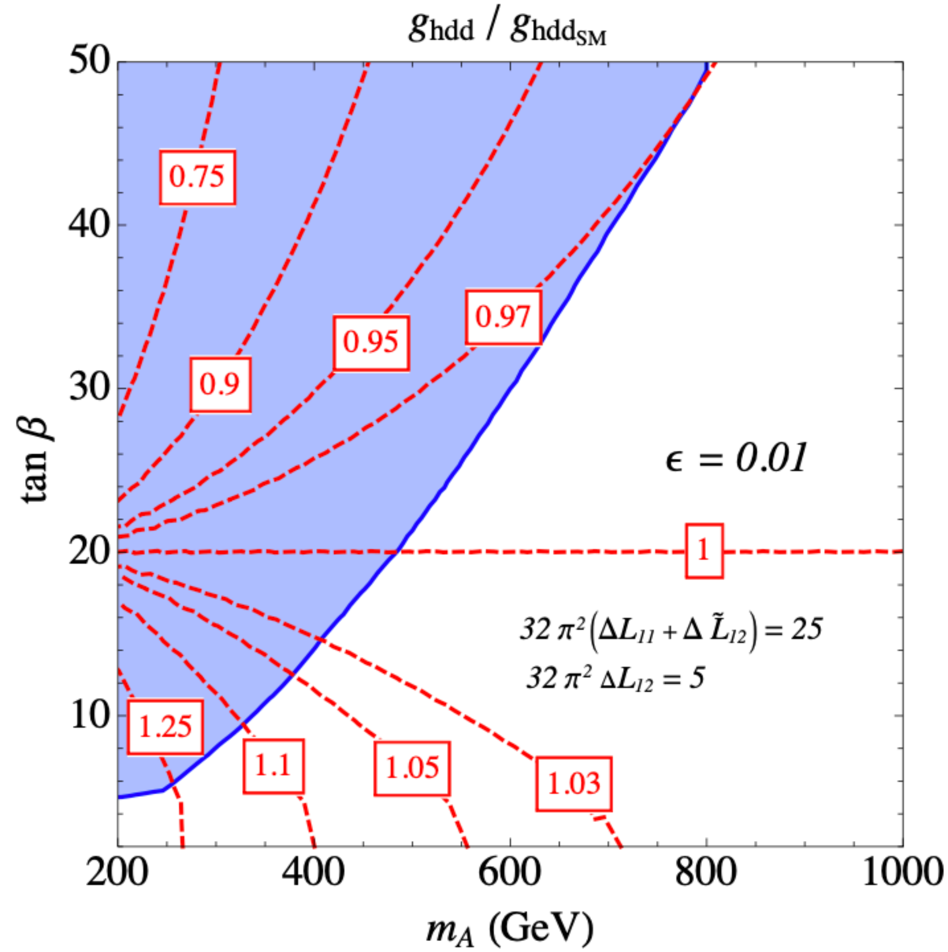
In MSSM it usually happens at moderate tanβ:



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

Carena, IL, Shah, Wagner: 1310.2248

- Some benchmarks for alignment at tanβ = 20 and 30:



In the infamous "Wedge region," O(10%) deviation is allowed for m_A~ 400 GeV.

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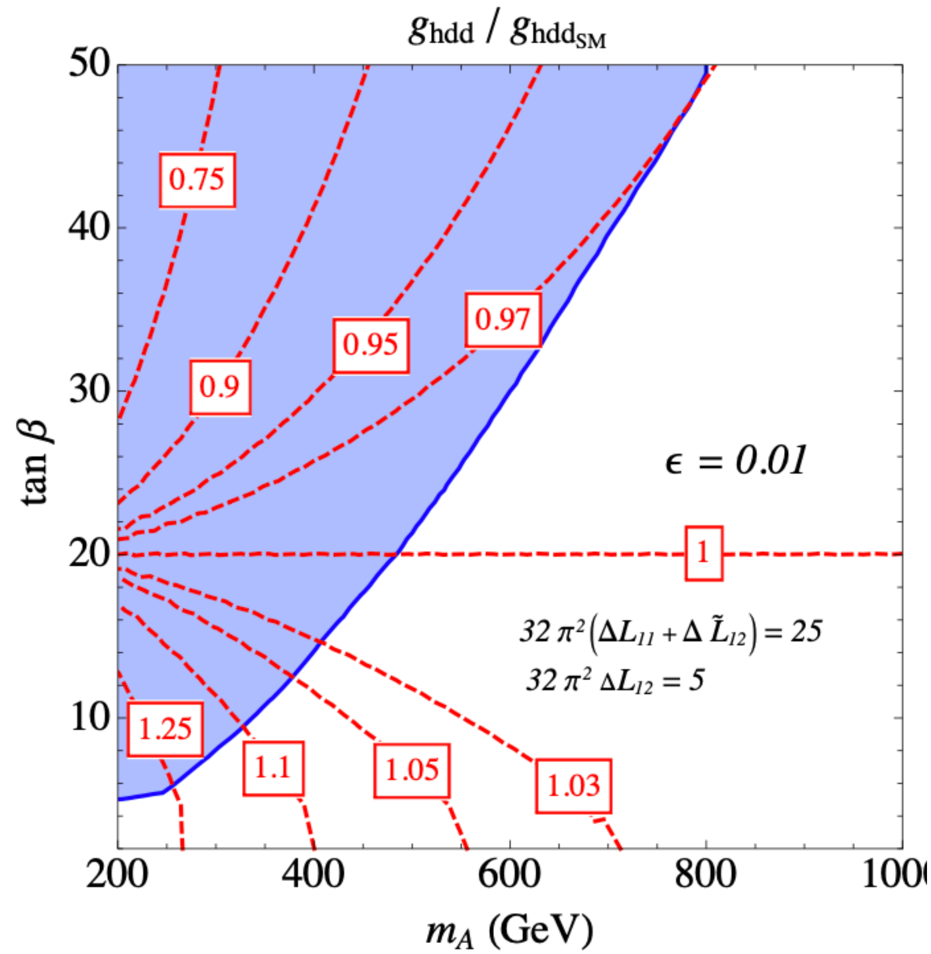
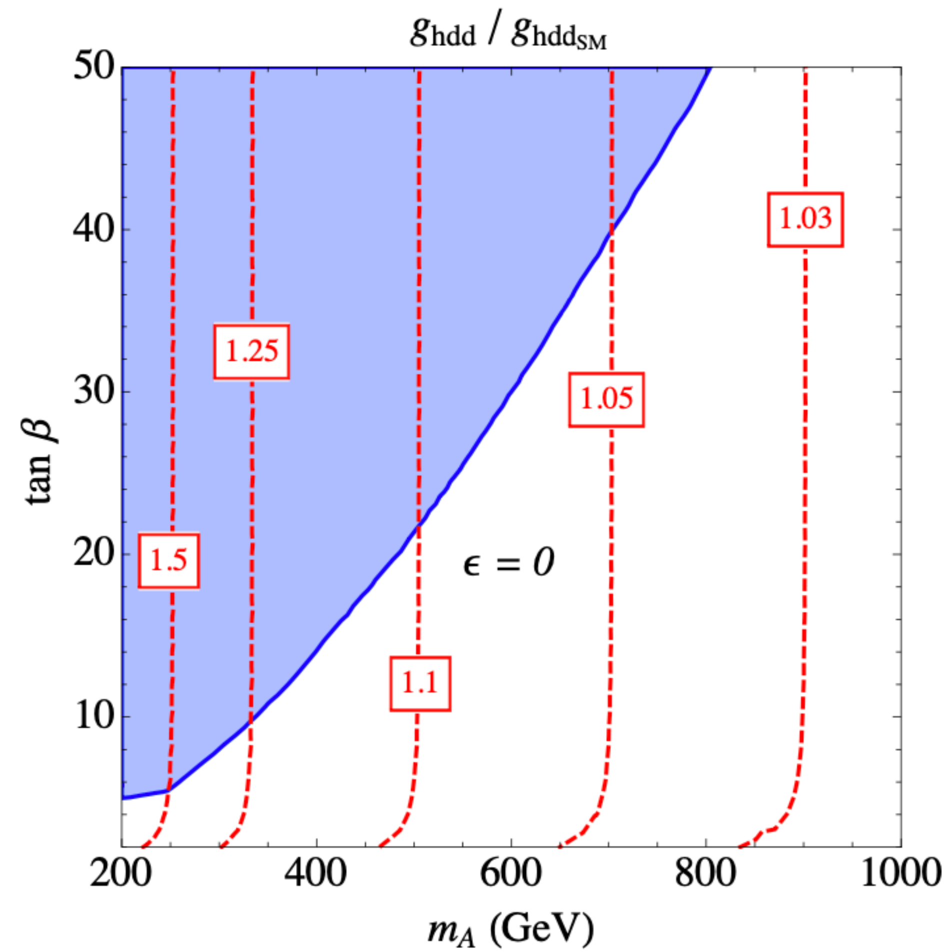
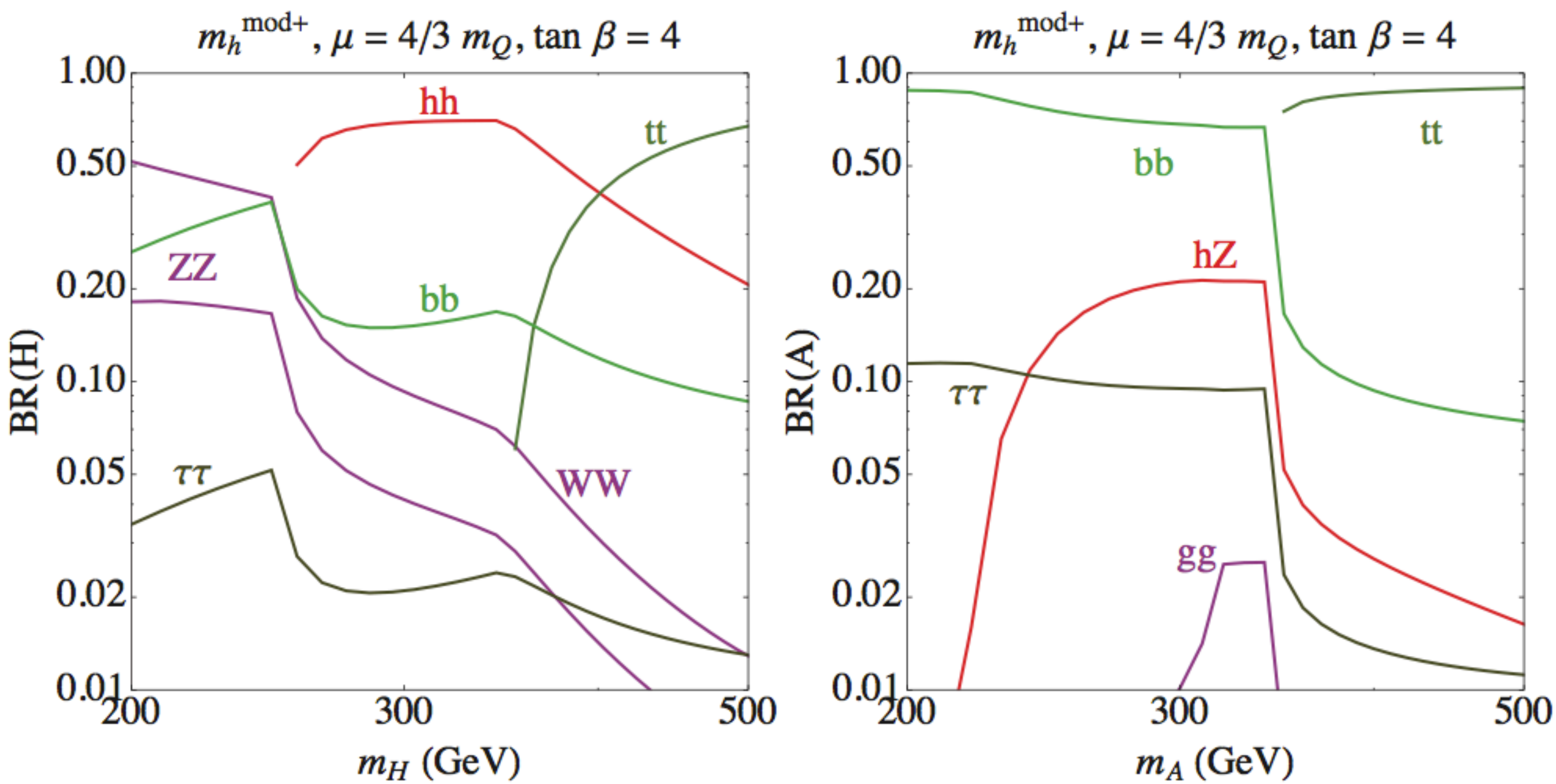




In the infamous "Wedge region," O(10%) deviation is allowed for m_A~ 400 GeV.

To the contrary, this is not the case in the decoupling limit.

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

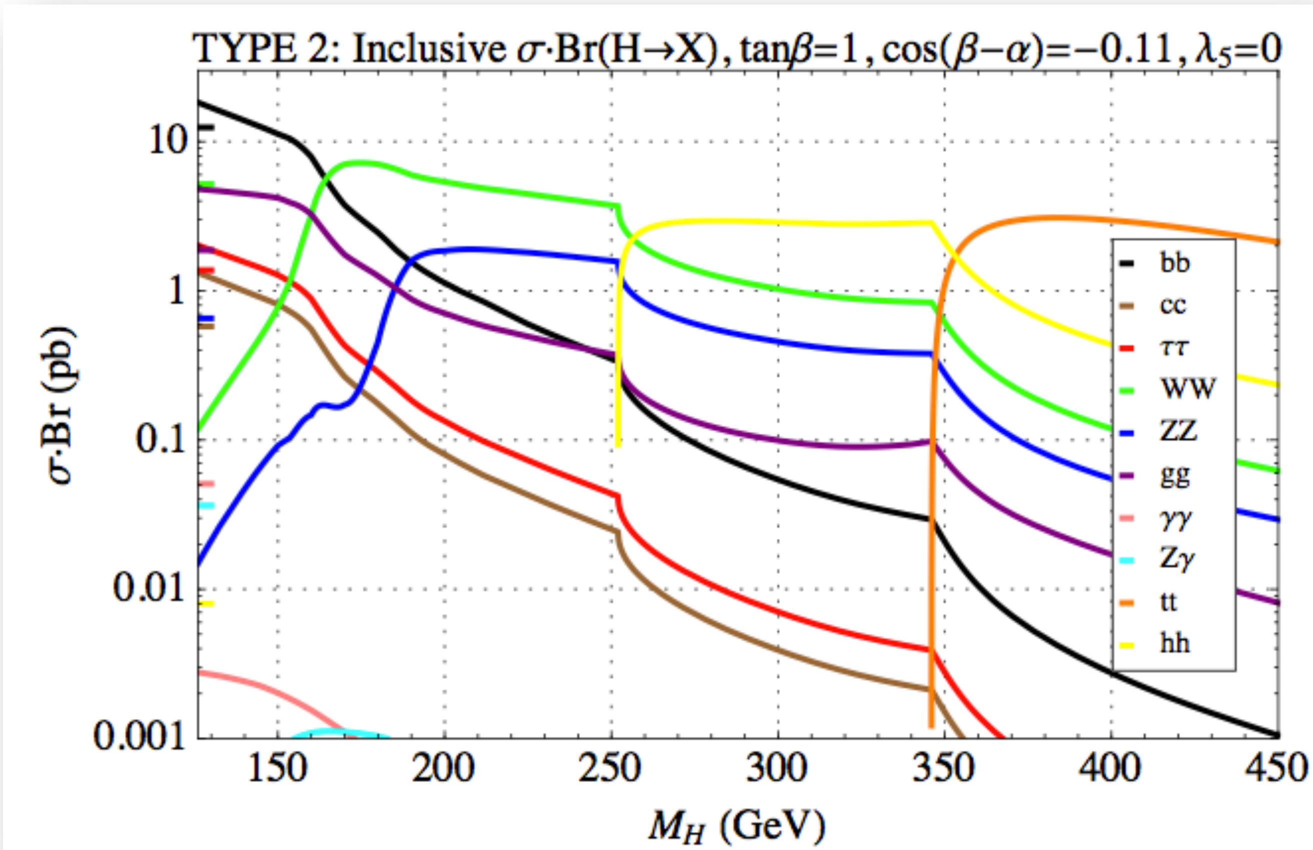


Dominant decay channels are WW, hh and tt, which are different from the most considered bb and tau tau!

Carena, Haber, IL, Shah and Wagner: 1410.4969

The same decay patterns of the heavy Higgs bosons hold in generic 2HDM:

Craig, Galloway, Thomas:1305.2424



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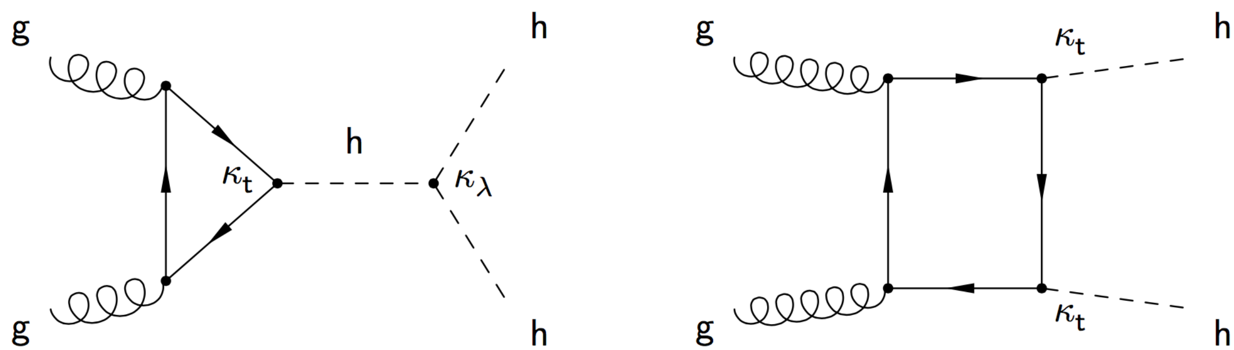
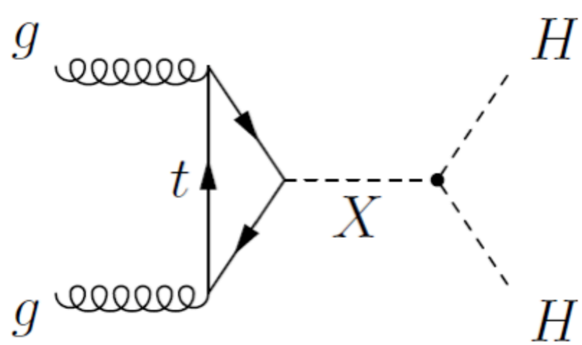
The other prominent decay channel is di-Higgs final states.

In the SM this channel provides a unique handle to measuring Higgs self-couplings:



In "Alignment without decoupling", new heavy scalars could appear in this channel:



Higgs Alignment in CP-violating 2HDMs

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

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

Haber+collaborators: 2001.01430

Different choices of parameters now truly represent physically distinct theories!

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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:

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- 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 :

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

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

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- 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

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

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

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

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

- 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:

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

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

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

Haber+collaborators: 2001.01430

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.

Haber+collaborators: 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:

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

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

Small departures from alignment can be parameterized by writing $\theta_{13} = \pi/2 + \epsilon$, $\epsilon \ll 1$,

$$\widetilde{R} = \begin{pmatrix} -\epsilon\, c_{12} & -s_{12} & -c_{12}(1-\epsilon^2/2) \\ -\epsilon\, s_{12} & c_{12} & -s_{12}(1-\epsilon^2/2) \\ 1-\epsilon^2/2 & 0 & -\epsilon \end{pmatrix} . \qquad (11)$$

- 9 input parameters

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

Low, Shah and Wang:2012.00773

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:

$$\begin{aligned} \mathrm{CPC1}: \;\; & \mathrm{Im}[\tilde{Z}_5] = \mathrm{Im}[\tilde{Z}_6] = \mathrm{Im}[\tilde{Z}_7] = 0 \\ \mathrm{CPC2}: \;\; & \mathrm{Im}[\tilde{Z}_5] = \mathrm{Re}[\tilde{Z}_6] = \mathrm{Re}[\tilde{Z}_7] = 0 \end{aligned}$$

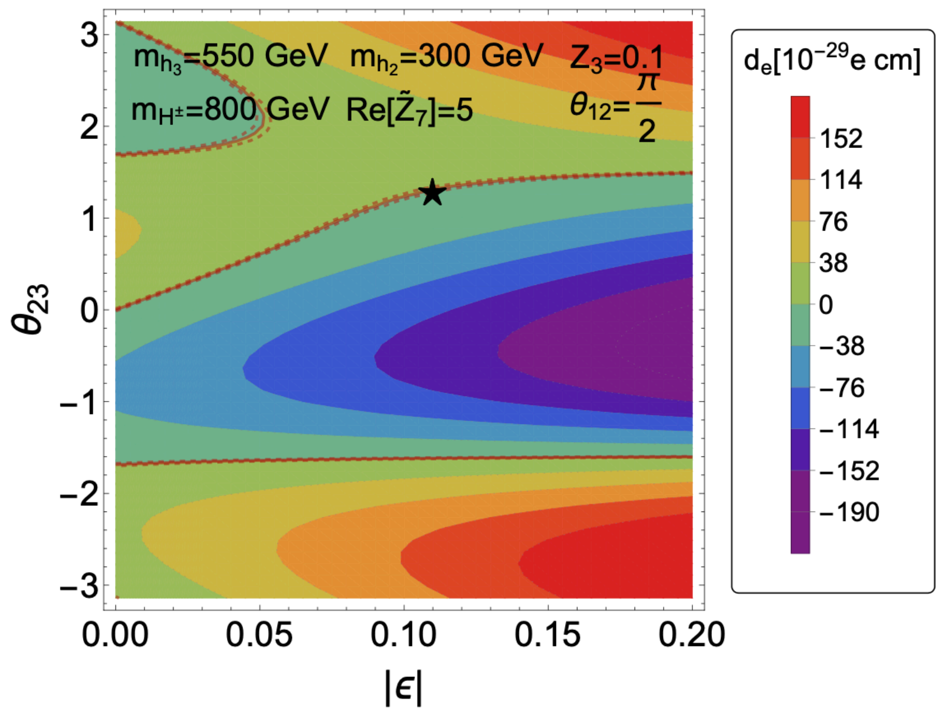
- In the CP-limit, there are two CP-even scalars (SM-like Higgs and H) and one CP-odd scalar (A). Only the two CP-even scalars could mix.

- 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

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

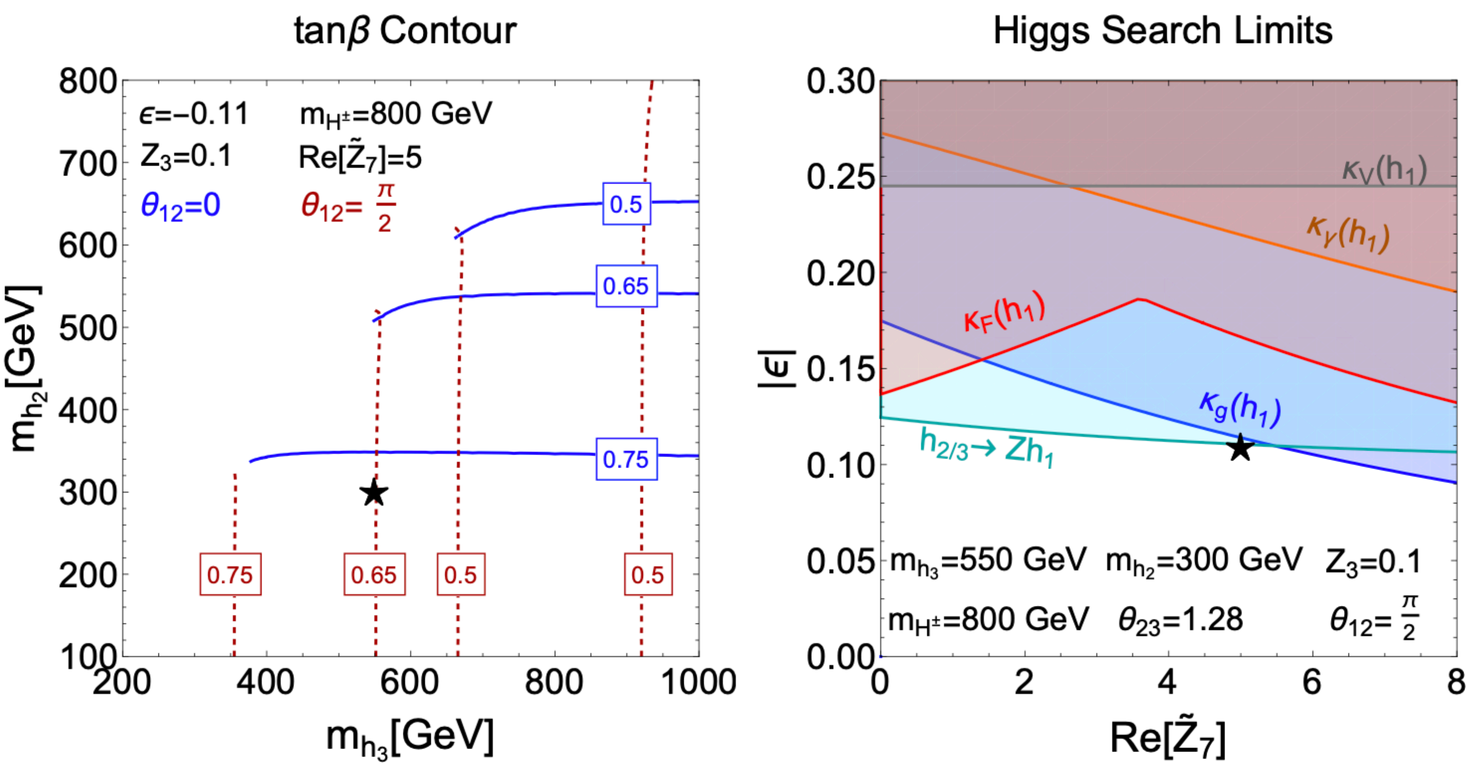
- In CPC 2, the SM-like Higgs has a small mixture with the CP-even component in H_2. In this case the CP-limit is independent of the alignment limit!



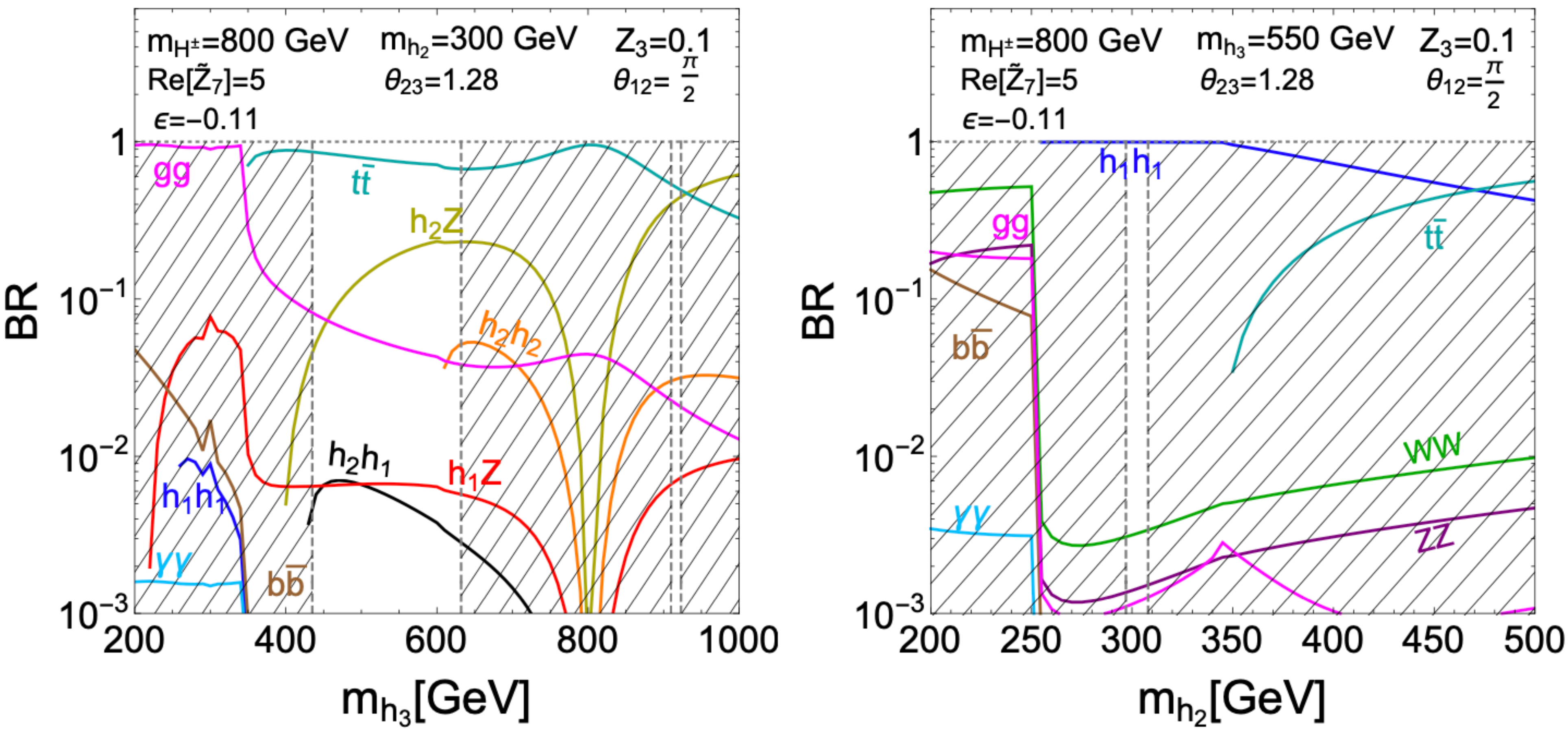
Collider phenomenology

$$\{Z_3, \mathrm{Re}[\tilde{Z}_7], \theta_{12}, \theta_{23}, \epsilon\} = \{0.1, 5, \pi/2, 1.28, -0.11\},$$
$$\{m_{h_3}, m_{h_2}, m_{H^\pm}\} = \{550, 300, 800\}\ \mathrm{GeV}\ . \qquad (21)$$

With these parameters, h_3 is mostly CP-odd, while h_2 and h_1 are mostly CP-even.



- Heavy Higgs decays



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

$$\mathrm{BR}(h_3 \ \rightarrow \ h_2 h_1) \sim 1\%$$

$$\mathrm{BR}(h_2 \rightarrow h_1 h_1) \sim 100\%$$

- 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!

$$\sigma(gg \to h_2) \simeq 5.9 \text{ pb} , \qquad \sigma(gg \to h_3) \simeq 11 \text{ pb}$$

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

$$N(h_3 \to h_2 h_1 \to h_1 h_1 h_1) = 1.7 \times 10^5$$

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!