CP violation in light of the LHC Higgs signal

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B.G., O. M. Ogreid and P. Osland

- "Diagnosing CP properties of the 2HDM", JHEP **1401**, 105 (2014),
- "Measuring CP violation in Two-Higgs-Doublet models in light of the LHC Higgs data", arXiv:1409.7265, to appear in JHEP,
- "CP violating effects in the ZZZ and ZWW within the Two-Higgs-Doublet Model", in progress

CP violation in 2HDM

Motivations for 2HDM:

- Baryon asymmetry and Sakharov conditions for baryogenesis
  - Baryon number non-conservation,
  - C- and CP-violation,
  - Thermal inequilibrium,

  Extra sources of the CP-violation are required

- Possibility of large (tree-level generated) FCNC, e.g. $t \to cH$ decays, interesting non-standard flavour physics

- 2HDM provide a framework for light new physics that is easily tolerated by the Higgs boson discovery.
  see e.g.
  B. Dumont, J. F. Gunion, Y. Jiang and S. Kraml, "Constraints on and future prospects for Two-Higgs-Doublet Models in light of the LHC Higgs signal", Phys. Rev. D **90**, 035021 (2014) [arXiv:1405.3584 [hep-ph]].

The 2HDM potential:

$$
\begin{aligned}
V(\Phi_1,\Phi_2) &= -\frac{1}{2}\left\{m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{H.c.}\right]\right\} + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 \\
&\quad + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
&\quad + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{H.c.}\right] + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\left[(\Phi_1^\dagger\Phi_2) + \text{H.c.}\right] \\
&= Y_{a\bar{b}}\Phi_{\bar{a}}^\dagger\Phi_b + \frac{1}{2}Z_{a\bar{b}c\bar{d}}(\Phi_{\bar{a}}^\dagger\Phi_b)(\Phi_{\bar{c}}^\dagger\Phi_d)
\end{aligned}
$$

Yukawa couplings:

$$
\mathcal{L}_Y^{(q)} = \bar{Q}_L\left(\tilde{\Gamma}_1\tilde{\Phi}_1 + \tilde{\Gamma}_2\tilde{\Phi}_2\right)u_R + \bar{Q}_L\left(\Gamma_1\Phi_1 + \Gamma_2\Phi_2\right)d_R + \text{H.c.}
$$

then

$$
M_u = -\tilde{\Gamma}_1\langle\tilde{\Phi}_1\rangle - \tilde{\Gamma}_2\langle\tilde{\Phi}_2\rangle \qquad M_d = -\Gamma_1\langle\Phi_1\rangle - \Gamma_2\langle\Phi_2\rangle
$$

The type II model:
$\mathbb{Z}_2$ softly broken (by $m_{12}^2 \neq 0$): $\Phi_1 \to -\Phi_1$ and $d_R \to -d_R \Rightarrow \lambda_6 = \lambda_7 = 0$, $\tilde{\Gamma}_1 = \Gamma_2 = 0$

In an arbitrary basis, the vevs may be complex, and the Higgs-doublets can be written

$$\Phi_j = e^{i\xi_j} \begin{pmatrix} \varphi_j^+ \\ (v_j + \eta_j + i\chi_j)/\sqrt{2} \end{pmatrix}, \quad j = 1, 2.$$

Here v_j are real numbers, so that $v_1^2 + v_2^2 = v^2$. The fields η_j and χ_j are real. The phase difference between the two vevs is defined as

$$\xi \equiv \xi_2 - \xi_1.$$

Next, let's define the Goldston bosons G_0 and $G^\pm$ by an orthogonal rotation

$$\begin{pmatrix} G_0 \\ \eta_3 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} \qquad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \varphi_1^\pm \\ \varphi_2^\pm \end{pmatrix}$$

where $s_\beta \equiv \sin\beta$ and $c_\beta \equiv \cos\beta$ for $\tan\beta \equiv v_2/v_1$. Then G_0 and $G^\pm$ become the massless Goldstone fields. $H^\pm$ are the charged scalars.

The model contains three neutral scalar mass-eigenstates, which are linear compositions of the η_i,

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix},$$

with the 3×3 orthogonal rotation matrix R satisfying

$$R\mathcal{M}^2 R^{\mathrm{T}} = \mathcal{M}^2_{\mathrm{diag}} = \mathrm{diag}(M_1^2, M_2^2, M_3^2),$$

and with $M_1 \leq M_2 \leq M_3$. A convenient parametrization of the rotation matrix R is

$$R = R_3 R_2 R_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_3 & s_3 \\ 0 & -s_3 & c_3 \end{pmatrix} \begin{pmatrix} c_2 & 0 & s_2 \\ 0 & 1 & 0 \\ -s_2 & 0 & c_2 \end{pmatrix} \begin{pmatrix} c_1 & s_1 & 0 \\ -s_1 & c_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_1\, c_2 & s_1\, c_2 & s_2 \\ -(c_1\, s_2\, s_3 + s_1\, c_3) & c_1\, c_3 - s_1\, s_2\, s_3 & c_2\, s_3 \\ -c_1\, s_2\, c_3 + s_1\, s_3 & -(c_1\, s_3 + s_1\, s_2\, c_3) & c_2\, c_3 \end{pmatrix}$$

CP violation and invariants under $U(2)$ basis rotations

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \to \begin{pmatrix} \bar{\Phi}_1 \\ \bar{\Phi}_2 \end{pmatrix} = e^{i\psi} \begin{pmatrix} \cos\theta & e^{-i\xi}\sin\theta \\ -e^{i\chi}\sin\theta & e^{i(\chi-\xi)}\cos\theta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}.$$

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- G. C. Branco, L. Lavoura and J. P. Silva, "CP Violation", Int. Ser. Monogr. Phys. 103, 1 (1999).

$$\begin{aligned}
\mathrm{Im}\, J_1 &\equiv -\frac{2}{v^2}\mathrm{Im}\left[\hat{v}^*_{\bar{a}} Y_{a\bar{b}} Z^{(1)}_{b\bar{d}} \hat{v}_d\right] \\
\mathrm{Im}\, J_2 &\equiv \frac{2}{v^4}\mathrm{Im}\left[\hat{v}^*_{\bar{b}} \hat{v}^*_{\bar{c}} Y_{b\bar{e}} Y_{c\bar{f}} Z_{e\bar{a}f\bar{d}} \hat{v}_a \hat{v}_d\right] \\
\mathrm{Im}\, J_3 &\equiv \mathrm{Im}\left[\hat{v}^*_{\bar{b}} \hat{v}^*_{\bar{c}} Z^{(1)}_{b\bar{e}} Z^{(1)}_{c\bar{f}} Z_{e\bar{a}f\bar{d}} \hat{v}_a \hat{v}_d\right]
\end{aligned}$$

In any 2HDM, CP is conserved
if and only if
the three invariants J_1, J_2 and J_3 are all real.

For $\lambda_6 = \lambda_7 = 0$ and real vev's:

$$\begin{aligned}
\mathrm{Im}\, J_1 &= -\frac{v_1^2 v_2^2}{v^4}(\lambda_1 - \lambda_2)\mathrm{Im}\,\lambda_5 \\
\mathrm{Im}\, J_2 &= -\frac{v_1^2 v_2^2}{v^8}\Big[\left((\lambda_1-\lambda_3-\lambda_4)^2 - |\lambda_5|^2\right) v_1^4 + 2(\lambda_1-\lambda_2)\mathrm{Re}\,\lambda_5 v_1^2 v_2^2 \\
&\qquad - \left((\lambda_2-\lambda_3-\lambda_4)^2 - |\lambda_5|^2\right) v_2^4\Big]\,\mathrm{Im}\,\lambda_5 \\
\mathrm{Im}\, J_3 &= \frac{v_1^2 v_2^2}{v^4}(\lambda_1 - \lambda_2)(\lambda_1+\lambda_2+2\lambda_4)\mathrm{Im}\,\lambda_5
\end{aligned}$$

Thus, CP conservation requires

$$\mathrm{Im}\, J_1 = \mathrm{Im}\, J_2 = \mathrm{Im}\, J_3 = 0.$$

- CPC1: $v_1 = 0$
- CPC2: $v_2 = 0$
- CPC3: $\mathrm{Im}\,\lambda_5 = 0$
- CPC4: $\lambda_1 = \lambda_2$ and $v_1 = v_2$
- CPC5: $\lambda_1 = \lambda_2$ and $(\lambda_1 - \lambda_3 - \lambda_4)^2 = |\lambda_5|^2$

Explicite CP violation and invariants under $U(2)$ basis rotations

In any 2HDM, CP is conserved explicitly in the scalar potential
if and only if
the following invariants are vanishing.

For $\lambda_6 = \lambda_7 = 0$ and real vev's:

$$
\begin{aligned}
I_{Y3Z} &\equiv \mathrm{Im}\left[Z^{(1)}_{a\bar{c}} Z^{(1)}_{e\bar{b}} Z_{b\bar{e}c\bar{d}} Y_{d\bar{a}}\right] = 0 \\
I_{2Y2Z} &\equiv \mathrm{Im}\left[Y_{a\bar{b}} Y_{c\bar{d}} Z_{b\bar{a}d\bar{f}} Z^{(1)}_{f\bar{c}}\right] = \frac{1}{4}(\lambda_1 - \lambda_2)\mathrm{Im}\ \left[(m^2_{12})^2 \lambda^*_5\right] \\
I_{3Y3Z} &\equiv \mathrm{Im}\left[Z_{a\bar{c}b\bar{d}} Z_{c\bar{e}d\bar{g}} Z_{e\bar{h}f\bar{q}} Y_{g\bar{a}} Y_{h\bar{b}} Y_{q\bar{f}}\right] \\
&= -\frac{1}{8}(m^2_{11} - m^2_{22})\left[(\lambda_1 - \lambda_3 - \lambda_4)(\lambda_2 - \lambda_3 - \lambda_4) - |\lambda_5|^2\right]\mathrm{Im}\ \left[(m^2_{12})^2 \lambda^*_5\right] \\
I_{6Z} &\equiv \mathrm{Im}\left[Z_{a\bar{b}c\bar{d}} Z^{(1)}_{b\bar{f}} Z^{(1)}_{d\bar{h}} Z_{f\bar{a}j\bar{k}} Z_{k\bar{j}m\bar{n}} Z_{n\bar{m}h\bar{c}}\right] = 0
\end{aligned}
$$

Spontaneous CP violation and invariants under $U(2)$ basis rotations

In the case when

$$I_{Y3Z} = I_{2Y2Z} = I_{3Y3Z} = I_{6Z} = 0,$$

CP is either conserved or broken spontaneously.

If, in addition, at least one of the J_i is complex, then the CP violation is spontaneous.

For CP to be broken *spontaneously* it is necessary that the following five conditions are satisfied simultaneously (failure to do so means the model is CP conserving):

- $v_1 \neq 0$
- $v_2 \neq 0$
- $\mathrm{Im}\,\lambda_5 \neq 0$
- $\lambda_1 \neq \lambda_2$ or $v_1 \neq v_2$
- $\lambda_1 \neq \lambda_2$ or $(\lambda_1 - \lambda_3 - \lambda_4)^2 \neq |\lambda_5|^2$

In addition, one or both of the following conditions ($I_{2Y2Z} = 0$ and/or $I_{3Y3Z} = 0$) must be satisfied (otherwise the CP violation would be explicit):

- SCPV1: $\mathrm{Im}\,\left[(m_{12}^2)^2 \lambda_5^*\right] = 0$
- SCPV2: $\lambda_1 = \lambda_2,\; m_{11}^2 = m_{22}^2$

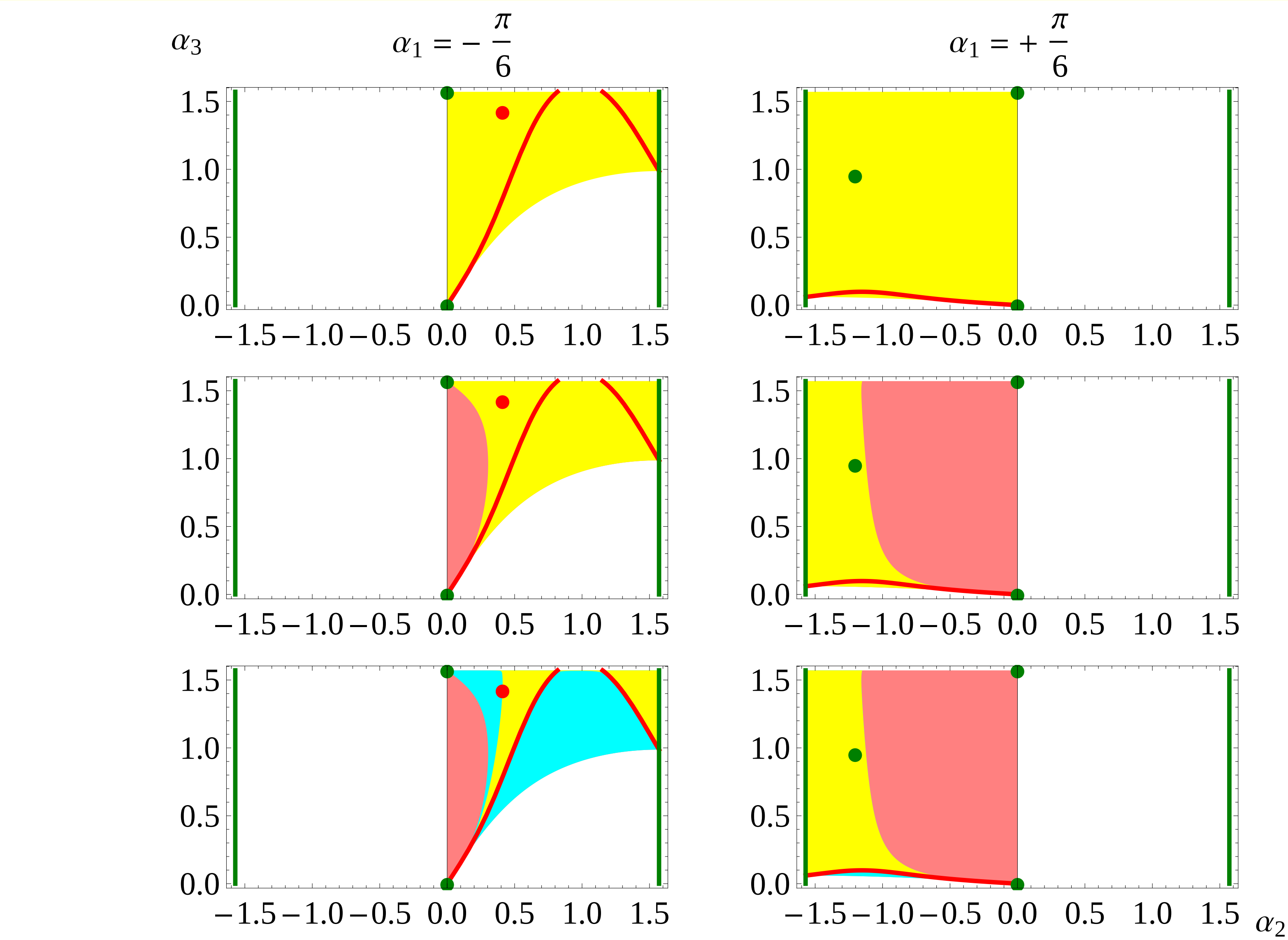


Figure 1: For $\tan\beta = 2$, and two values of α_1 (left: $\alpha_1 = -\pi/6$, right: $\alpha_1 = +\pi/6$), the top panels show the allowed regions (yellow) in the α_2–α_3 space after imposing the constraint $M_3 > M_2$. Red curves correspond to parameters that satisfy the condition SCPV1, while red dots satisfy the condition SCPV2. Both of these indicate spontaneous CP violation. Green lines and dots indicate locations of CP conservation. Middle panels: the positivity constraint is also imposed (pink region disallowed). Bottom panels: additionally, the global minimum constraint is imposed (cyan region disallowed).

Couplings

$$H_i Z_\mu Z_\nu : \quad \frac{ig^2}{2\cos^2\theta_{\mathsf{W}}} e_i\, g_{\mu\nu}, \qquad H_i W_\mu^+ W_\nu^- : \quad \frac{ig^2}{2} e_i\, g_{\mu\nu}$$

where

$$e_i \equiv v_1 R_{i1} + v_2 R_{i2}$$

In terms of the mixing angles

$$\begin{aligned}
e_1 &= \quad v\cos\alpha_2\cos(\beta-\alpha_1) \\
e_2 &= \quad v[\cos\alpha_3\sin(\beta-\alpha_1) - \sin\alpha_2\sin\alpha_3\cos(\beta-\alpha_1)] \\
e_3 &= -v[\sin\alpha_3\sin(\beta-\alpha_1) + \sin\alpha_2\cos\alpha_3\cos(\beta-\alpha_1)]
\end{aligned}$$

Note that

$$e_1^2 + e_2^2 + e_3^2 = v^2.$$

Couplings:

$$(Z^\mu H_i H_j): \quad \frac{g}{2v\cos\theta_{\mathsf{W}}}\epsilon_{ijk}e_k(p_i-p_j)^\mu,$$

$$H_i H^- H^+: \quad -iq_i$$

where

$$\begin{aligned} q_i \quad = \quad & \frac{2e_i}{v^2}M_{H^\pm}^2 - \frac{R_{i2}v_1 + R_{i1}v_2 - R_{i3}vt_\xi}{v_1 v_2 c_\xi}\mu^2 + \frac{g_i - R_{i3}v^3 t_\xi}{v^2 v_1 v_2}M_i^2 + \frac{R_{i3}v^3}{2v_1 v_2 c_\xi^2}\mathrm{Im}\,\lambda_5 \\ & - \frac{v^2\left(R_{i3}vt_\xi - R_{i2}v_1 + R_{i1}v_2\right)}{2v_2^2 c_\xi}\mathrm{Re}\,\lambda_6 - \frac{v^2\left(R_{i3}vt_\xi + R_{i2}v_1 - R_{i1}v_2\right)}{2v_1^2 c_\xi}\mathrm{Re}\,\lambda_7 \end{aligned}$$

and $g_i \equiv v_1^3 R_{i2} + v_2^3 R_{i1}$.

CP conservation:

The invariants could be expressed in terms of masses and coupling constants, so that the conditions for CP conservation could be rewritten as:

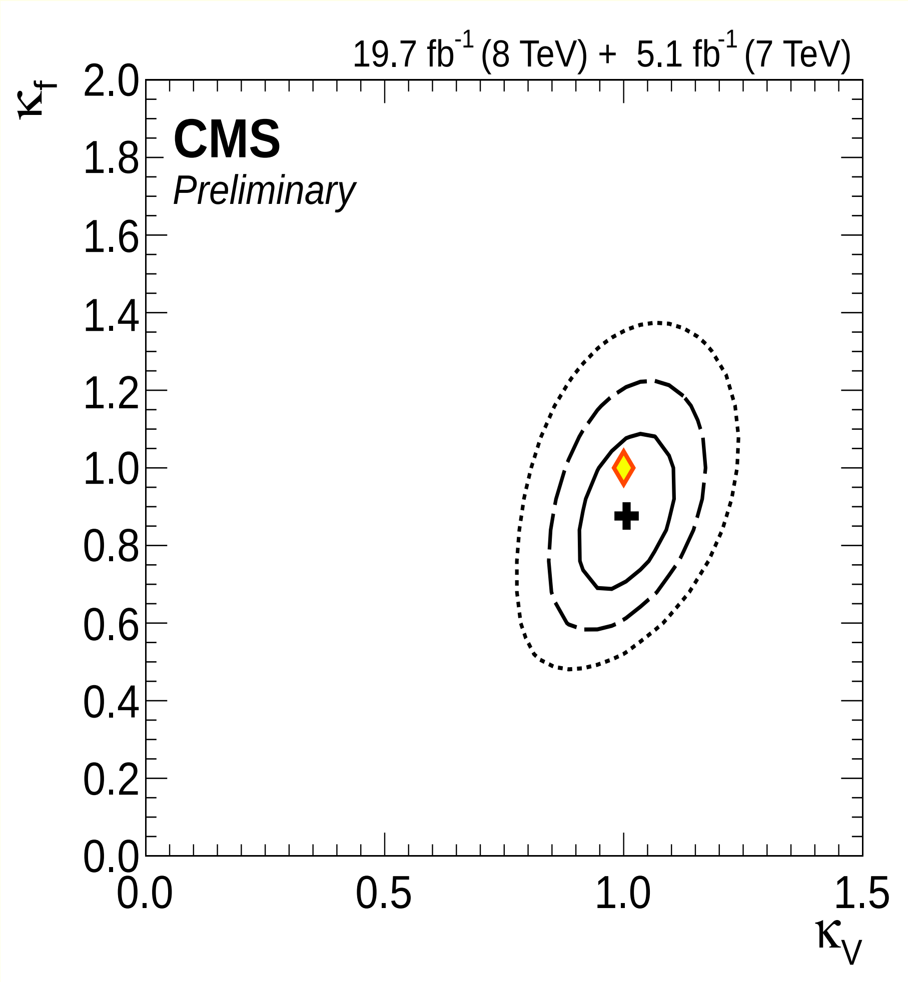
$$\begin{aligned}
\mathrm{Im}\, J_1 &= \frac{1}{v^5}\sum_{i,j,k}\epsilon_{ijk}M_i^2 e_i e_j q_k = 0 \\
\mathrm{Im}\, J_2 &= \frac{e_1 e_2 e_3}{v^9}\sum_{i,j,k}\epsilon_{ijk}M_i^4 M_k^2 = 0 \\
\mathrm{Im}\, J_{30} &= \frac{1}{v^5}\sum_{i,j,k}\epsilon_{ijk}M_i^2 q_i e_j q_k = 0.
\end{aligned}$$

CP conservation:

The conditions for CP conservation could be rewritten as:

$$
\begin{aligned}
\mathrm{Im}\, J_1 &= \frac{1}{v^5}\left[M_1^2 e_1(e_2 q_3 - e_3 q_2) + M_2^2 e_2(e_3 q_1 - e_1 q_3) + M_3^2 e_3(e_1 q_2 - e_2 q_1)\right] = 0 \\
\mathrm{Im}\, J_2 &= \frac{e_1 e_2 e_3}{v^9}(M_2^2 - M_1^2)(M_3^2 - M_2^2)(M_1^2 - M_3^2) = 0 \\
\mathrm{Im}\, J_{30} &= \frac{1}{v^5}\left[M_1^2 q_1(e_2 q_3 - e_3 q_2) + M_2^2 q_2(e_3 q_1 - e_1 q_3) + M_3^2 q_3(e_1 q_2 - e_2 q_1)\right] = 0
\end{aligned}
$$

The alignment limit



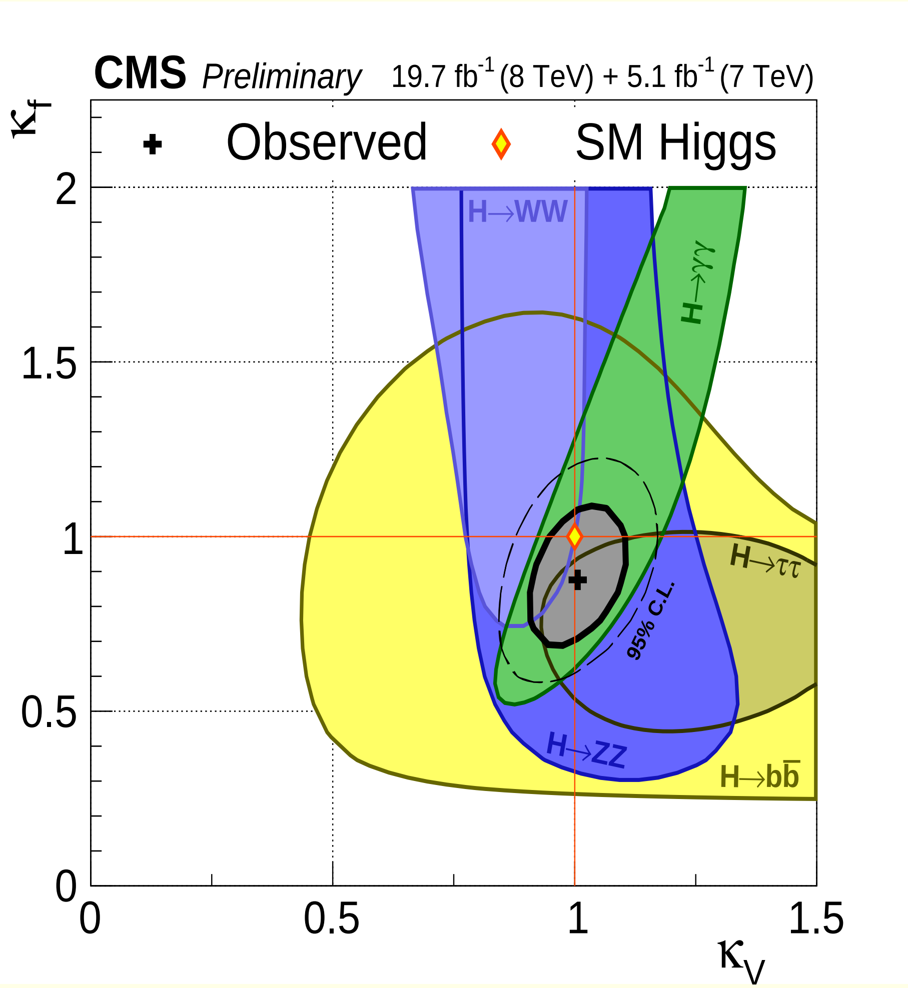


Figure 2: CMS PAS HIG-14-009: Results of 2D likelihood scans for the (κ_V, κ_f). Left: the solid, dashed, and dotted contours show the 68%, 95%, and 99.7% CL regions, respectively. Right: the 68% CL contours for individual channels and for the overall combination (thick curve), the dashed contour bounds the 95% CL region.

The LHC Higgs data suggest that HZZ and HW^+W^- couplings are close to the SM prediction.

$$\Downarrow$$

$$H_i Z_\mu Z_\nu : \quad \frac{ig^2}{2\cos^2\theta_{\mathsf{W}}} e_i \, g_{\mu\nu}, \qquad H_i W_\mu^+ W_\nu^- : \quad \frac{ig^2}{2} e_i \, g_{\mu\nu}$$

We define (within 2HDM) the alignment limit as $e_1 = v$

Then

$$e_1^2 + e_2^2 + e_3^2 = v^2 \qquad \Rightarrow \qquad e_2 = e_3 = 0$$

Note that no assumption has been made concerning the mass scale of beyond the SM physics: M_2, M_3 and μ^2 defined as

$$\mathrm{Re}\, m_{12}^2 = \frac{2v_1 v_2}{v^2}\mu^2.$$

The coupling of H_1 to a pair of vector bosons, e_1, could be written as follows:

$$e_1 = v\cos(\alpha_2)\cos(\alpha_1 - \beta)$$

The most general solution of the alignment condition $e_1 = v$, $e_2 = 0$, $e_3 = 0$:

$$\alpha_2 = 0 \qquad \alpha_1 = \beta$$

The rotation matrix in this case becomes

$$R = \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta & 0 \\ -s_\beta\, c_3 & c_\beta\, c_3 & s_3 \\ s_\beta\, s_3 & -c_\beta\, s_3 & c_3 \end{pmatrix}$$

Note that the mixing matrix could be written in this case as

$$R = R_3 R_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_3 & s_3 \\ 0 & -s_3 & c_3 \end{pmatrix} \begin{pmatrix} c_\beta & s_\beta & 0 \\ -s_\beta & c_\beta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Does the alignment limit allow for CP-violation?

Couplings:

In the alignment limit Z couples only to H_2H_3:

$$(Z^\mu H_i H_j): \quad \frac{g}{2v\cos\theta_{\mathrm{W}}}\epsilon_{ijk}e_k(p_i - p_j)^\mu \neq 0 \ \text{ only if } \ \mathrm{i}=2 \ \text{ and } \ \mathrm{j}=3$$

Couplings between H_i and H^+H^- are given in the alignment limit (for $\xi = 0$) by:

$$\begin{aligned}
q_1 &= \frac{1}{v}\left(2M_{H^\pm}^2 - 2\mu^2 + M_1^2\right) \\
q_2 &= +c_3\left[\frac{(c_\beta^2 - s_\beta^2)}{vc_\beta s_\beta}(M_2^2 - \mu^2) + \frac{v}{2s_\beta^2}\mathrm{Re}\,\lambda_6 - \frac{v}{2c_\beta^2}\mathrm{Re}\,\lambda_7\right] + s_3\frac{v}{2c_\beta s_\beta}\mathrm{Im}\,\lambda_5, \\
q_3 &= -s_3\left[\frac{(c_\beta^2 - s_\beta^2)}{vc_\beta s_\beta}(M_3^2 - \mu^2) + \frac{v}{2s_\beta^2}\mathrm{Re}\,\lambda_6 - \frac{v}{2c_\beta^2}\mathrm{Re}\,\lambda_7\right] + c_3\frac{v}{2c_\beta s_\beta}\mathrm{Im}\,\lambda_5
\end{aligned}$$

In the alignment limit

$$
\begin{aligned}
\mathrm{Im}\, J_1 &= \frac{1}{v^5}\left[M_1^2 e_1(e_2q_3 - e_3q_2) + M_2^2 e_2(e_3q_1 - e_1q_3) + M_3^2 e_3(e_1q_2 - e_2q_1)\right] \to 0 \\
\mathrm{Im}\, J_2 &= \frac{e_1e_2e_3}{v^9}(M_2^2 - M_1^2)(M_3^2 - M_2^2)(M_1^2 - M_3^2) \to 0 \\
\mathrm{Im}\, J_{30} &= \frac{1}{v^5}\left[M_1^2 q_1(e_2q_3 - e_3q_2) + M_2^2 q_2(e_3q_1 - e_1q_3) + M_3^2 q_3(e_1q_2 - e_2q_1)\right] \\
&\to \frac{e_1q_2q_3}{v^3}(M_3^2 - M_2^2)
\end{aligned}
$$

- Note that $e_1 = v$ implies no CP violation in H_iVV couplings ($\mathrm{Im}\, J_2 = 0$), the only possible CP violation may appear in cubic scalar couplings $H_2H^+H^-$ and $H_3H^+H^-$, proportional to q_2 and q_3, respectively.

- The necessary condition for CP violation is that both $H_2H^+H^-$ *and* $H_3H^+H^-$ must exist *together* with non-zero ZH_2H_3 vertex. The latter implies that for CP invariance either H_2 or H_3 would have to be odd under CP, on the other hand if *both* of them couple to H^+H^- (that is CP even), then there is no way to preserve CP.

$R\mathcal{M}^2R^{\mathrm{T}} = \mathcal{M}^2_{\mathrm{diag}} = \mathrm{diag}(M_1^2, M_2^2, M_3^2)$, in the case $\lambda_6 = \lambda_7 = 0$

$$\mathcal{M}^2_{13} = \tan\beta\mathcal{M}^2_{23}$$

$$\Downarrow$$

$$M_1^2R_{13}(R_{12}\tan\beta - R_{11}) + M_2^2R_{23}(R_{22}\tan\beta - R_{21}) + M_3^2R_{33}(R_{32}\tan\beta - R_{31}) = 0$$

$$\Downarrow$$

alignment limit ($\alpha_2 = 0, \alpha_1 = \beta$) $\Rightarrow$ $\boxed{(M_2^2 - M_3^2)s_3c_3s_\beta = 0}$

$$\Downarrow$$

- $M_2 \neq M_3$, but $\alpha_3 = 0, \pm\pi/2$, then $q_3 = 0, q_2 = 0$ ($\mathrm{Im}\,\lambda_5 = 0$), respectively, so no CP violation, or

- $M_2 = M_3$, therefore $\mathrm{Im}\,J_{30} = 0$, so again no CP violation,

If $\lambda_6 = \lambda_7 = 0$

there is no extra CP violation within 2HDM in the alignment limit

In order to investigate possible symmetries behind the alignment it is necessary to formulate the $e_1 = v$ condition in terms of the potential parameters.

$$R\mathcal{M}^2 R^{\mathrm{T}} = \mathcal{M}^2_{\mathrm{diag}} = \mathrm{diag}(M_1^2, M_2^2, M_3^2),$$

for $R = R_3 R_\beta$ where $R_\beta \equiv R_1|_{\alpha_1=\beta}$.

$$\Downarrow$$

$$\mathcal{M}^2 = R_\beta^T R_3^T \mathcal{M}^2_{\mathrm{diag}} R_3 R_\beta.$$

$$\Downarrow$$

$$\begin{aligned}
\mathcal{M}^2_{13} &= -t_\beta \mathcal{M}^2_{23} \\
\left(t_\beta^{-1} - t_\beta\right) \mathcal{M}^2_{12} &= (\mathcal{M}^2_{11} - \mathcal{M}^2_{22})
\end{aligned}$$

$$
\begin{aligned}
v_2^2 \mathrm{Im}\,\left(e^{i\xi}\lambda_7\right) + v_2 v_2 \mathrm{Im}\,\left(e^{2i\xi}\lambda_5\right) + v_1^2 \mathrm{Im}\,\left(e^{i\xi}\lambda_6\right) &= 0, \\
v_2^4 \mathrm{Re}\,\left(e^{i\xi}\lambda_7\right) + v_2^3 v_1(-\lambda_2 + \lambda_{345}) + 3v_2^2 v_1^2 \mathrm{Re}\,\left[e^{i\xi}(\lambda_6 - \lambda_7)\right] + & \\
+ v_2 v_1^3(\lambda_1 - \lambda_{345}) - v_1^4 \mathrm{Re}\,\left(e^{i\xi}\lambda_6\right) &= 0
\end{aligned}
$$

where $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \mathrm{Re}\,\left(e^{2i\xi}\lambda_5\right)$.

In the CP-conserving limit, with $\xi = 0$, $\mathrm{Im}\,\lambda_5 = \mathrm{Im}\,\lambda_6 = \mathrm{Im}\,\lambda_7 = 0$, we reproduce the single alignment condition found recently by P. S. B. Dev and A. Pilaftsis, “Maximally Symmetric Two Higgs Doublet Model with Natural Standard Model Alignment,” arXiv:1408.3405.

If the alignment conditions should be satisfied for any value of v_1, v_2 and ξ, then the following constraints must be fulfilled:

$$
\lambda_1 = \lambda_2 = \lambda_3 + \lambda_4, \;\; \lambda_5 = \lambda_6 = \lambda_7 = 0
$$

- The alignment conditions can not be satisfied for any v_1, v_2 and ξ together with CP violation.

- For CP to be violated, $\tan\beta$ must be properly tuned.

Partial conclusions:

- The observation of the SM-like Higgs boson at the LHC implies (within the 2HDM with $\mathbb{Z}_2$ softly broken) vanishing CP violation in the scalar potential.

- The above conclusion could be realized either by large masses of the extra Higgs bosons (the decoupling regime) or by alignment with relatively light extra Higgs bosons (the case discussed here). For both possibilities the H_1VV coupling is SM-like and CP violation disappears (within the 2HDM with $\mathbb{Z}_2$ softly broken).

- **In order for CP violation to be present in the scalar potential, the LHC data favours the generic 2HDM with no $\mathbb{Z}_2$ symmetry (thus allowing for non-zero λ_6 and/or λ_7). A consequence of that would be an interesting possibility of large (tree-level generated) FCNC in some Yukawa couplings.**

Numerical strategy and illustrations

Parameters:

- for 2HDM5 ($\mathbb{Z}_2$ imposed, so $\lambda_6 = \lambda_7 = 0$):

$$\mathcal{P}_5 \equiv \{M_{H^\pm}^2, \mu^2, M_1^2, M_2^2, v_1, v_2, \xi = 0, \alpha_1, \alpha_2, \alpha_3\}$$

- for 2HDM67 ($\mathbb{Z}_2$ not imposed, so $\lambda_6 \neq 0, \lambda_7 \neq 0$):

$$\mathcal{P}_{67} \equiv \{M_{H^\pm}^2, \mu^2, M_1^2, M_2^2, M_3^2, \mathrm{Im}\lambda_5, \mathrm{Re}\lambda_6, \mathrm{Re}\lambda_7, v_1, v_2, \xi = 0, \alpha_1, \alpha_2, \alpha_3\}$$

Plots shown in next slides have been obtained adopting the following strategy:

- 2HDM5 ($\mathbb{Z}_2$ imposed, so $\lambda_6 = \lambda_7 = 0$):
  - $M_{H^\pm}^2$, μ^2, M_2, $\tan\beta$ are fixed parameters
  - scan over $\alpha_1, \alpha_2, \alpha_3$ for chosen maximal deviation $\delta \equiv |e_1/v - 1|$ and imposing $M_1 < M_2 < M_3$, vacuum stability and unitarity.

- for 2HDM67 ($\mathbb{Z}_2$ not imposed, so $\lambda_6 \neq 0, \lambda_7 \neq 0$):
  - $M_{H^\pm}^2$, μ^2, M_2, M_3, and $\tan\beta$ are fixed parameters
  - scan over $\alpha_1, \alpha_2, \alpha_3$, $\mathrm{Im}\lambda_5, \mathrm{Re}\lambda_6, \mathrm{Re}\lambda_7$, for chosen maximal deviation $\delta \equiv |e_1/v - 1|$ and imposing $M_1 < M_2 < M_3$, vacuum stability and unitarity.

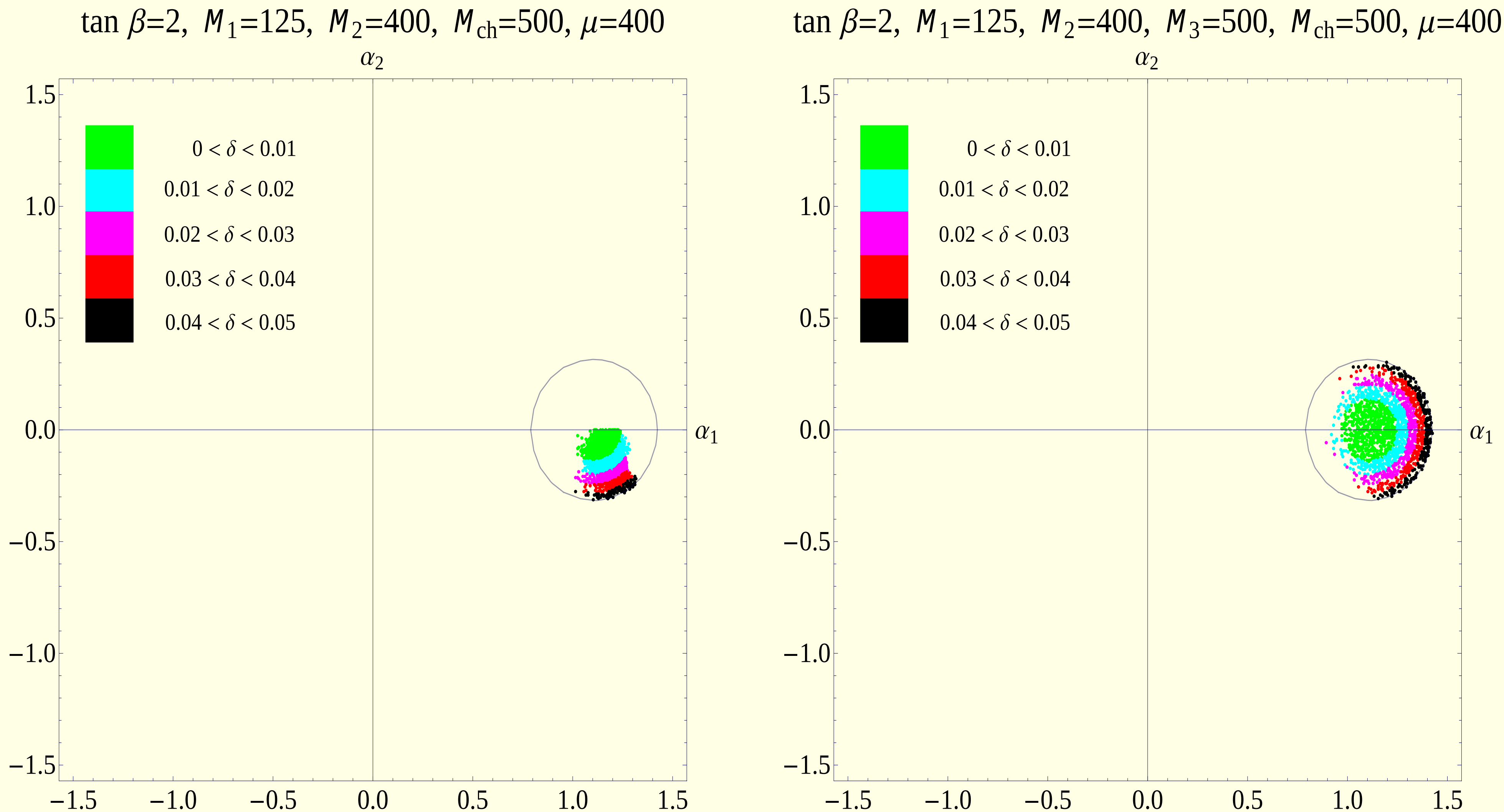


Figure 3: Allowed regions in the (α_1, α_2) space for $\tan\beta = 2$ corresponding to maximal deviation $\delta \equiv |e_1/v - 1| = 0.05$ within 2HDM5 ($\mathbb{Z}_2$ imposed) and 2HDM67, are shown in the left and right panels, respectively. Coloring corresponds to ranges of δ shown in the legend. Vacuum stability and unitarity constraints are satisfied. Parameters adopted are shown in the plot.

The goal is to see

How much CP violation remain
for a given maximal deviation $\boldsymbol{\delta \equiv |e_1/v - 1|}$ from the alignment limit?

$$\Downarrow$$

For points inside "circles" we calculate $\mathrm{Im}\, J_1$, $\mathrm{Im}\, J_2$ and $\mathrm{Im}\, J_{30}$

Figure 4: Correletion between $\mathrm{Im}\, J_1$ and the maximal deviation $\delta \equiv |e_1/v - 1| = 0.05$. Green and red dots correspond to 2HDM67 and 2HDM5, respectively.

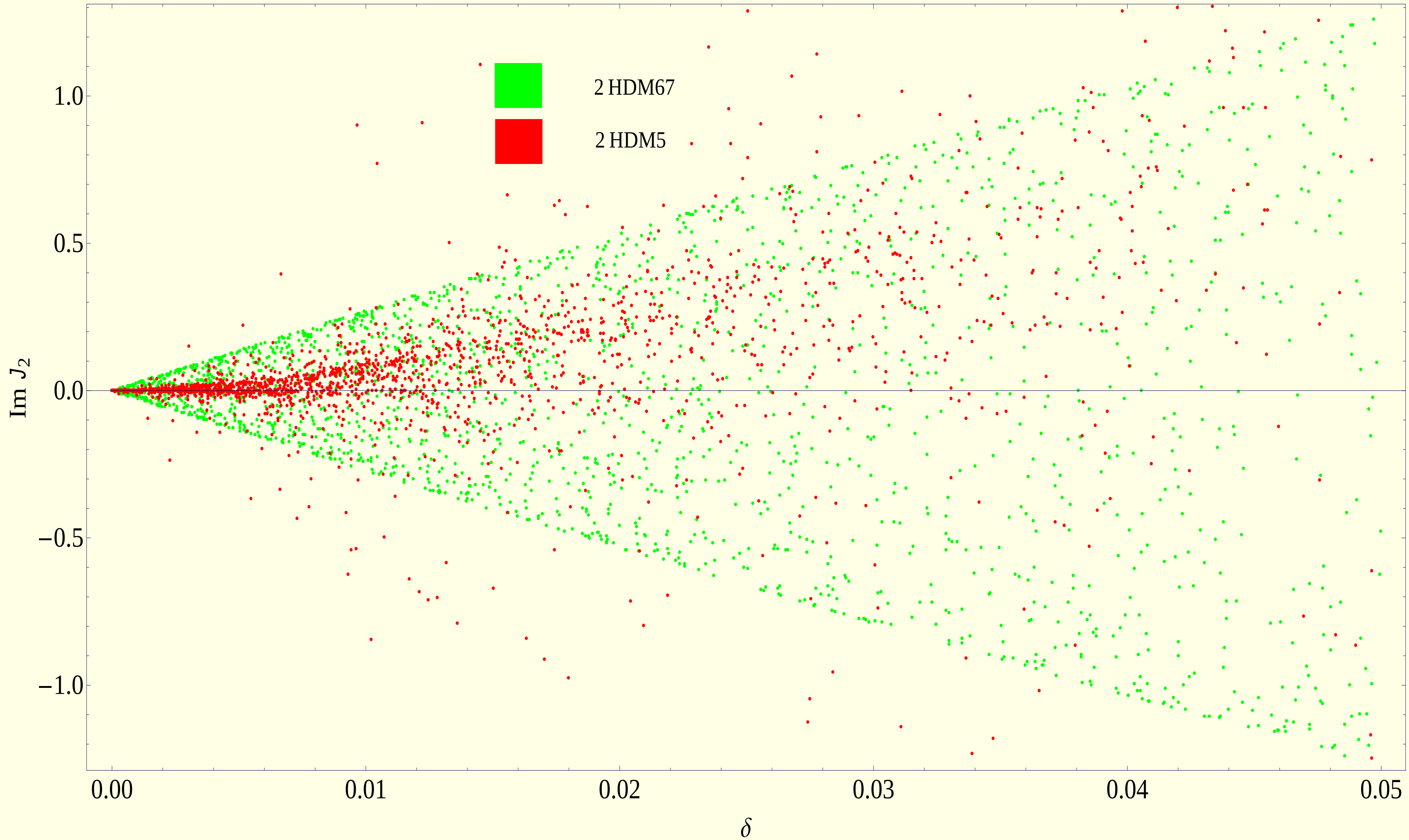


Figure 5: Correletion between $\mathrm{Im}\, J_2$ and the maximal deviation $\delta \equiv |e_1/v - 1| = 0.05$. Green and red dots correspond to 2HDM67 and 2HDM5, respectively.

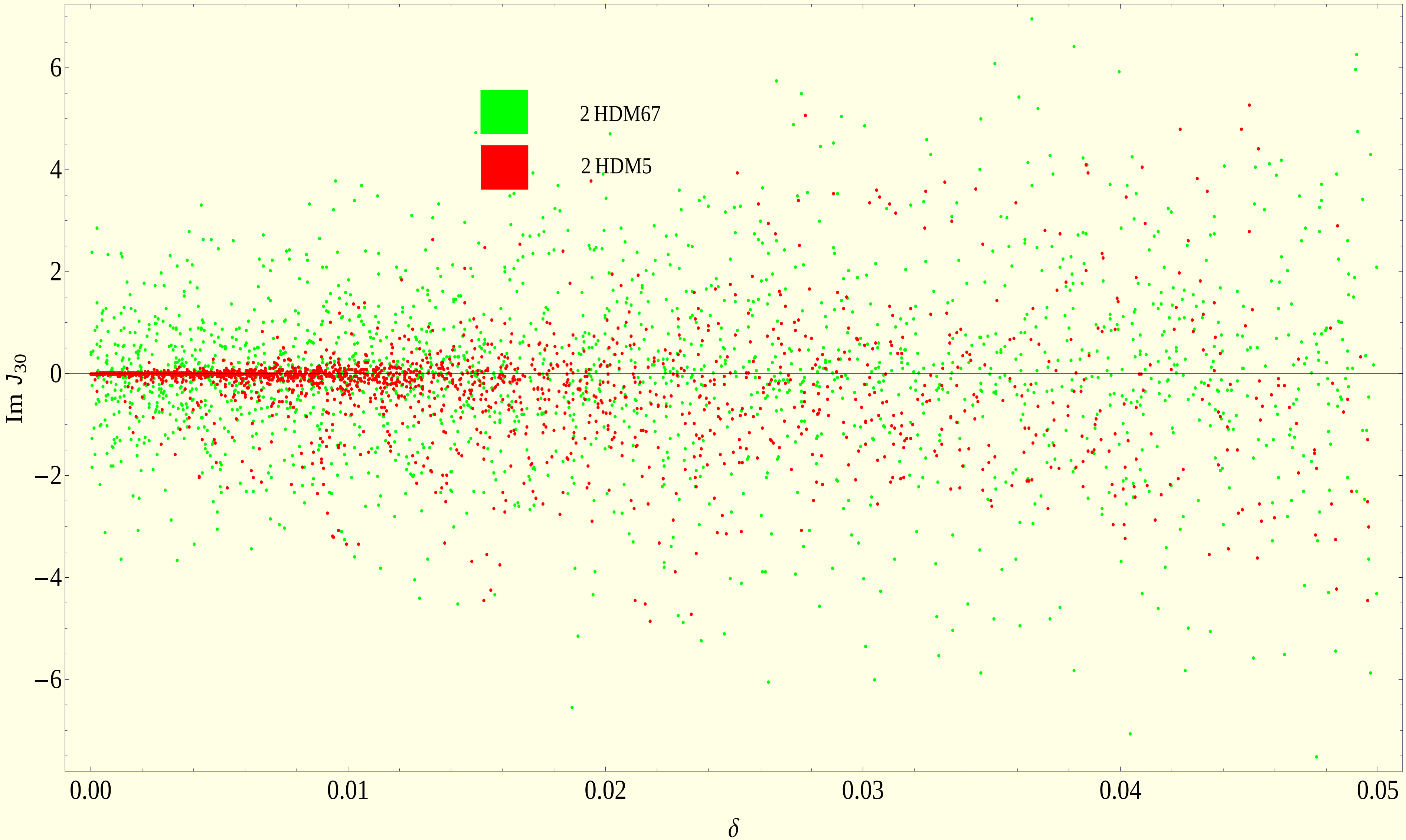


Figure 6: Correletion between $\mathrm{Im}\, J_{30}$ and the maximal deviation $\delta \equiv |e_1/v - 1| = 0.05$. Green and red dots correspond to 2HDM67 and 2HDM5, respectively.

Prospects for measuring CP violation

The alignment limit: $e_1 = v, e_2 = 0, e_3 = 0$

$$
\begin{aligned}
\mathrm{Im}\, J_1 &= \frac{1}{v^5}\sum_{i,j,k}\epsilon_{ijk}M_i^2 e_i e_j q_k \to 0 \\
\mathrm{Im}\, J_2 &= \frac{e_1 e_2 e_3}{v^9}\sum_{i,j,k}\epsilon_{ijk}M_i^4 M_k^2 \to 0 \\
\mathrm{Im}\, J_{30} &= \frac{1}{v^5}\sum_{i,j,k}\epsilon_{ijk}M_i^2 q_i e_j q_k \to \frac{e_1 q_2 q_3}{v^3}(M_3^2 - M_2^2)
\end{aligned}
$$

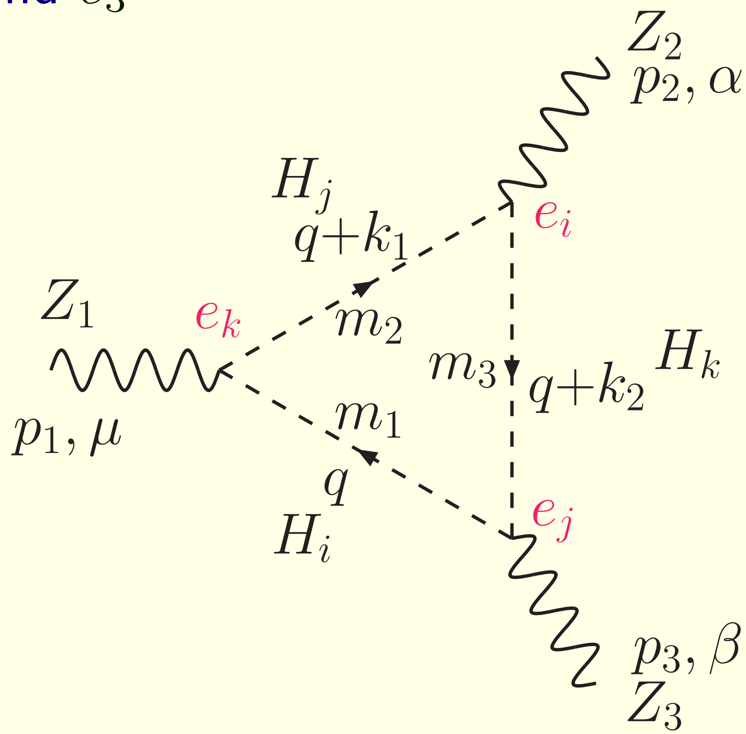
$$H_i Z_\mu Z_\nu : \quad \frac{ig^2}{2\cos^2\theta_{\mathrm{W}}} e_i\, g_{\mu\nu}$$

$$(Z^\mu H_i H_j) : \quad \frac{g}{2v\cos\theta_{\mathrm{W}}}\epsilon_{ijk} e_k (p_i - p_j)^\mu$$

$$H_i H^- H^+ : \quad -iq_i$$

$\mathrm{Im}\, J_2 = \frac{e_1 e_2 e_3}{v^9} \sum_{i,j,k} \epsilon_{ijk} M_i^4 M_k^2 \to 0$

Couplings needed: e_1, e_2 and e_3



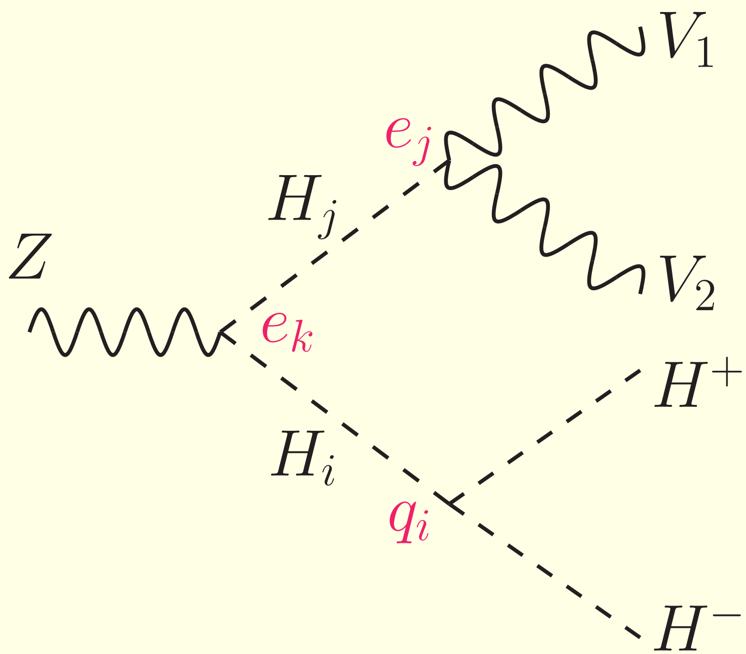
$$\propto \left[f_4^{CPV} (p_1^\alpha g^{\mu\beta} + p_1^\beta g^{\mu\alpha}) + f_5^{CPC} \epsilon^{\mu\alpha\beta\rho} \ell^\rho \right],$$

where $\ell \equiv p_2 - p_3$ (Z_2 and Z_3 are on-shell) .

$$f_4^Z \propto \mathrm{Im}\, J_2$$

$\mathrm{Im}\, J_1 = \frac{1}{v^5} \sum_{i,j,k} \epsilon_{ijk} M_i^2 e_i e_j q_k \to 0$

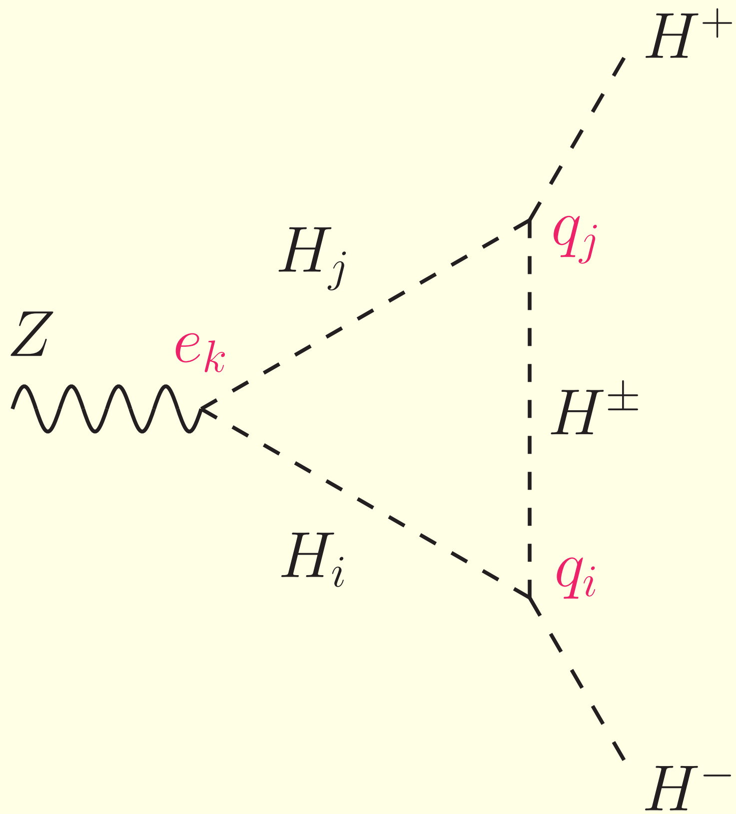
Couplings needed: e_1, e_2 and q_3



If $\mathrm{Im}\, J_2 = 0$ then $\mathcal{M}|_{\mathrm{diag}} \propto \mathrm{Im}\, J_1$

$$\mathrm{Im}\, J_{30} = \frac{1}{v^5} \sum_{i,j,k} \epsilon_{ijk} M_i^2 q_i e_j q_k \to \frac{e_1 q_2 q_3}{v^3}(M_3^2 - M_2^2)$$

Couplings needed: e_1, q_2 and q_3



$$\propto \left[A^{CPV} p_Z^\mu + B^{CPC} (p_+ - p_-)^\mu\right]$$

If $\mathrm{Im}\, J_1 = \mathrm{Im}\, J_2 = 0$ then $A^{CPV} \propto \mathrm{Im}\, J_{30}$

Summary

- 2HDM allows for extra sources of CP-violation that might be useful to explain baryon asymmetry.
- We have defined the alignment limit as $e_1 = v$, so that H_1 couples to VV as in the SM.
- In the alignment limit there is no CP-violation if $\lambda_6 = \lambda_7 = 0$ ($\mathbb{Z}_2$ imposed).
- The requirement of extra sources of CP-violation in the presence of light extra scalars favours the most general 2HDM with $\lambda_6 \neq 0$ and $\lambda_7 \neq 0$ (no $\mathbb{Z}_2$ symmetry).
- The requirement of extra sources of CP-violation in the presence of light extra scalars implies an interesting possibility of large FCNC that couple to Higgs bosons (in progress).
- ZZZ and ZH^+H^- suitable for tests of CPV in the scalar sector.
- Presented results are insensitive to the structure of Yukawa couplings (type independent).