On distinguishing the direct and spontaneous CP violation in 2HDM

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Content

Motivation

- Sources of CP violation – a fundamental question in particle physics
- CP conservation – the Lagrangian **and** vacuum conserve CP
- CP violation – explicit or spontaneous
- 2HDM allows both the explicit and spontaneous violation of CP symmetry
- CP violating weak-basis invariants
- To distinguish spontaneous and explicit violation – comparison of various invariants

2 Higgs Doublet Model

- We consider the general 2 Higgs Doublet Model (without fermions):

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{gauge} + \left(D_\mu \Phi_1\right)^\dagger \left(D^\mu \Phi_1\right) + \left(D_\mu \Phi_2\right)^\dagger \left(D^\mu \Phi_2\right) - V, \\
V &= \tfrac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \tfrac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4\left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\
&\quad + \left[\tfrac{1}{2}\lambda_5\left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_1^\dagger \Phi_2\right) + \lambda_6\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_1^\dagger \Phi_2\right) + \lambda_7\left(\Phi_2^\dagger \Phi_2\right)\left(\Phi_1^\dagger \Phi_2\right) + H.c.\right] \\
&\quad - \tfrac{1}{2} m_{11}^2\left(\Phi_1^\dagger \Phi_1\right) - \tfrac{1}{2} m_{22}^2\left(\Phi_2^\dagger \Phi_2\right) - \tfrac{1}{2} m_{12}^2\left(\Phi_1^\dagger \Phi_2\right) - \tfrac{1}{2}(m_{12}^2)^*\left(\Phi_2^\dagger \Phi_1\right)
\end{aligned}
$$

- Scalar doublets in the Higgs (Georgi) Basis (ie. $\langle \Phi_2 \rangle = 0$):

$$
\Phi_1 = \begin{pmatrix} G^+ \\ \frac{v + \eta_1 + iG^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{\eta_2 + iA}{\sqrt{2}} \end{pmatrix}
$$

- There are 2 charged physical Higgs fields: H^+, H^- and 3 neutral:
  - in case of CP conservation: h, H, A
  - in case of CP violation: h_1, h_2, h_3

CP transformation

- In Lagrangian we must identify CP-invariant part in order to determine the CP transformation

[Branco, Lee '66]

- Let us consider the simplest CP transformation in 2HDM:

$$\Phi_1(\vec{x},t) \to \Phi_1^\dagger(-\vec{x},t), \qquad \Phi_2(\vec{x},t) \to \Phi_2^\dagger(-\vec{x},t)$$

- Under this transformation the fields transform as follows:

$$\text{CP-even: } \eta_{1,2} \to \eta_{1,2}, \qquad \text{CP-odd: } A \to -A$$

Conditions for CP violation

CP-odd weak-basis inviariants – invariant under weak basis transformation but change sign under CP transformation.

- Jarlskog invariant for quarks in SM (m_i - mass, V_{ij} - CKM matrix):

$$J \propto (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \times \mathrm{Im}(V_{ud} V_{cs} V_{us}^* V_{cd}^*)$$

If $J = 0$ then CP is conserved.

[Jarlskog '85]

- Invariant for scalars in 2HDM (m_i - mass, T_{ij} - elements of rotation matrix):

$$J_1 \propto (m_1^2 - m_2^2)(m_1^2 - m_3^2)(m_2^2 - m_3^2) T_{11} T_{21} T_{31}$$

$J_1 = 0 \not\Rightarrow$ CP conservation

[Lavoura '94]

J-invariants

- The squared mass matrix for neutral scalars (η_1, η_2, A) in the Higgs basis has following form:

In the Higgs basis: $\lambda_i \to \Lambda_i, m_{ij}^2 \to \mu_{ij}^2$

$$\begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{pmatrix} = \begin{pmatrix} v^2\Lambda_1 & v^2 \mathrm{Re}\,\Lambda_6 & -v^2 \mathrm{Im}\,\Lambda_6 \\ v^2 \mathrm{Re}\,\Lambda_6 & \left[v^2\Lambda_{345} - \mu_{22}^2\right]/2 & -v^2 \mathrm{Im}\,\Lambda_5/2 \\ -v^2 \mathrm{Im}\,\Lambda_6 & -v^2 \mathrm{Im}\,\Lambda_5/2 & \left[v^2\tilde{\Lambda}_{345} - \mu_{22}^2\right]/2 \end{pmatrix}$$

- The invariant constructed from mass matrix:

$$J_1 = M_{12}M_{13}(M_{22} - M_{33}) + M_{23}\left(M_{13}^2 - M_{12}^2\right) = -8v^6 \mathrm{Im}\left(\Lambda_5^* \Lambda_6^2\right)$$

  - M_{13} or M_{23} non-zero $\Rightarrow$ CP-mixing between states, CP violation
  - $M_{13} = M_{23} = 0 \Rightarrow$ no CP-mixing, yet possible CP violation

- Note that Λ_7 does not appear in mass matrix and it can appear only in interactions $\Rightarrow J_2, J_3$:

$$J_2 = -4v^4 \mathrm{Im}\left(\Lambda_5^* \Lambda_7^2\right), \qquad J_3 = 2\sqrt{2}v^3 \mathrm{Im}\left(\Lambda_7^* \Lambda_6\right)$$

J-invariants - summary

From mass matrix:	From interaction:
$J_1 \propto \mathrm{Im}\,(\Lambda_5^* \Lambda_6^2)$	$J_2 \propto \mathrm{Im}\,(\Lambda_5^* \Lambda_7^2)$, $J_3 \propto \mathrm{Im}\,(\Lambda_7^* \Lambda_6)$

- To have CP conserving model all J-invariants must be 0.
- CP violation:
  - If $J_1 \neq 0$ then there is mixing between neutral states of different CP properties and physical states h_1, h_2, h_3 have no defined CP.
  - If $J_1 = 0$ and $J_{2,3} \neq 0$ we have CP violation from interactions even if there is no mixing between states!
  - Note that J_i do not distinguish between spontaneous and explicit CP violation.
- Note that all that is valid not only in the Higgs Basis!

[Lavoura, Silva, Botella '94]

I-invariants

- Other invariants formed from the parameters of the potential:

$$V = Y_{a\bar{b}}\Phi^{\dagger}_{\bar{a}}\Phi_b + \frac{1}{2}Z_{a\bar{b}c\bar{d}}(\Phi^{\dagger}_{\bar{a}}\Phi_b)(\Phi^{\dagger}_{\bar{c}}\Phi_d)$$

$I_1 = \mathrm{Im}(Z^{(1)}_{a\bar{c}}Z^{(1)}_{e\bar{b}}Z_{b\bar{e}c\bar{d}}Y_{d\bar{a}})$ $\quad$ $I_2 = \mathrm{Im}(Y_{a\bar{b}}Y_{c\bar{d}}Z_{b\bar{a}d\bar{f}}Z^{(1)}_{f\bar{c}})$

$I_3 = \mathrm{Im}(Z_{a\bar{c}b\bar{d}}Z^{(1)}_{b\bar{f}}Z^{(1)}_{d\bar{h}}Z_{f\bar{a}j\bar{k}}Z_{k\bar{j}m\bar{n}}Z_{n\bar{m}h\bar{c}}),$ $\quad$ $I_4 = \mathrm{Im}(Z_{a\bar{c}b\bar{d}}Z_{c\bar{e}d\bar{g}}Z_{e\bar{h}f\bar{q}}Y_{g\bar{a}}Y_{h\bar{b}}Y_{q\bar{f}})$

- 4 invariants formed from quartic and quadratic parameters of V

- The **potential** is explicitly CP conserving $\Leftrightarrow$ all I_i are 0
$\Leftrightarrow$ there exists „real basis" of fields Φ_1, Φ_2 in which all λ_i, m^2_{ij} are real
$\Rightarrow$ CP symmetry can be conserved **or** violated spontaneously

- If $\exists I_i \neq 0$ then CP is explicitly violated.

[Branco; Haber, Gunion '05]

J- and I-invariants: a comparison

Model properties	J-invariants	I-invariants
CP explicitly violated	$\exists J_i \neq 0$	$\exists I_i \neq 0$
CP spontaneously violated	$\exists J_i \neq 0$	$\forall I_i = 0$
CP conserved	$\forall J_i = 0$	$\forall I_i = 0$

- if $\forall J_i = 0$ then we have CP conserving case
- if $\exists J_i \neq 0$ then we have CP violation
  - if $\forall I_i = 0$ then we have spontaneous CP violation
  - if $\exists I_i \neq 0$ then we have explicit CP violation

CP violation without mixing: $J_1 = 0$

▶ Let's consider a special case when $\mathrm{Im}\,\Lambda_5 = \mathrm{Im}\,\Lambda_6 = 0$. The neutral mass matrix in basis (η_1, η_2, A) is:

$$\begin{pmatrix} v^2\Lambda_1 & v^2\mathrm{Re}\,\Lambda_6 & 0 \\ v^2\mathrm{Re}\,\Lambda_6 & [v^2\Lambda_{345}-\mu_{22}^2]/2 & 0 \\ 0 & 0 & [v^2\tilde{\Lambda}_{345}-\mu_{22}^2]/2 \end{pmatrix} \Rightarrow J_1 \sim \mathrm{Im}(\Lambda_5^*\Lambda_6^2) = 0$$

▶ After diagonalization we get states h, H and A with defined CP properties - there is no mixing between states of different CP.

▶The interactions with gauge bosons are like in CP conserving case (α – mixing angle between η_1 and η_2, χ_i – relative coupling with respect to SM):

$$hW^+W^- \propto \chi_1^V = \cos\alpha, \quad HW^+W^- \propto \chi_2^V = \sin\alpha,$$

$$AW^+W^- \propto \chi_3^V = 0$$

▶ Note, that if there is a mixing then $\chi_3^V \neq 0$

CP violation without mixing - self-interactions

- $\text{Im}\,\Lambda_5 = \text{Im}\,\Lambda_6 = 0 \Rightarrow J_1 = 0$
- $\text{Im}\,\Lambda_7 \neq 0 \Rightarrow J_2, J_3 \neq 0$ - there is a sign of CP violation in the interaction!

$$AAA \propto -\text{Im}\Lambda_7 v, \qquad Ahh \propto -\text{Im}\Lambda_7 v \sin^2\alpha,$$

$$AHH \propto -\text{Im}\Lambda_7 v \cos^2\alpha, \qquad AhH \propto \text{Im}\Lambda_7 v \cos\alpha \sin\alpha,$$

$$AH^+H^- \propto -\text{Im}\Lambda_7 v$$

- No couplings with odd number of A in CP conserving case

- To conclude:
  - $J_1 = 0, J_{2,3} \neq 0$: there is a CP violation in the model.
  - To determine whenever it is spontaneous or explicit violation we need to use I-invariants.

Summary

- CP violation in 2HDM without fermions

- Study of sources of CP violation with focus on distinguishing explicit and spontaneous violation

- We found that both J_i and I_i are needed to distinguish sources

- Usual approach: CP violation $\Leftrightarrow$ mixing between states of different CP properties (true for soft violation of Z_2 symmetry)

- However, with CP conservation in the gauge interactions of scalars still possible CP violation in self-interactions
$\Rightarrow$ CP violation effects in vertices with odd number of A
(eg. $A \to H^+H^-$)