Symmetries in two-Higgs-doublet models

João P. Silva

ISEL & CFTP

Why I got interested

- There is no reason why there should be only one Higgs doublet

  ==> this is an experimental question

- Take n Higgs. Even in the Higgs potential alone

$$V_H = Y_{ab}(\Phi_a^\dagger \Phi_b) + \frac{1}{2} Z_{ab,cd}(\Phi_a^\dagger \Phi_b)(\Phi_c^\dagger \Phi_d),$$

  there are

$$n^2 + \frac{n^2(n^2+1)}{2} = \frac{n^2(n^2+3)}{2} \qquad (2, 14, 54, ...)$$

  parameters.

Why I got interested

- Cut the number of parameters through symmetries. What are the range of possibilities?
- What is the role of basis transformations?
- What about CP?

Collaborations with

- **Pedro Ferreira**
- **Luís Lavoura**
- **Howard Haber**
- **Markos Maniatis**
- **Otto Nachtmann**

and discussions with

- **Igor Ivanov**
- **Celso Nishi**
- **...**

Main ideas

- What are Generalized CP (GCP) symmetries?
- GCP in the scalar potential
- Extend GCP to the quark sector
  => only one single implementation is possible
  => unique model
- Unique model displays a new type of spontaneous CPV
- Model is under stress!

The scalar sector of the THDM

$$
\begin{aligned}
V_H &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right] \\
&\quad + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&\quad + \left[\tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{H.c.} \right],
\end{aligned}
$$

14 parameters

$$
V_H = Y_{ab} (\Phi_a^\dagger \Phi_b) + \tfrac{1}{2} Z_{ab,cd} (\Phi_a^\dagger \Phi_b)(\Phi_c^\dagger \Phi_d),
$$

$$
\begin{aligned}
Y_{ab} &= Y_{ba}^*, \\
Z_{ab,cd} \equiv Z_{cd,ab} &= Z_{ba,dc}^*.
\end{aligned}
$$

Basis transformations

$$\Phi_a \to \Phi'_a = U_{ab}\Phi_b,$$

$$v_a \to v'_a = U_{ab} v_b.$$

$$\begin{aligned} Y_{ab} &\to & Y'_{ab} = U_{a\alpha}\, Y_{\alpha\beta}\, U^*_{b\beta} = \left(U\, Y\, U^\dagger\right)_{ab}, \\ Z_{ab,cd} &\to & Z'_{ab,cd} = U_{a\alpha}\, U_{c\gamma}\, Z_{\alpha\beta,\gamma\delta}\, U^*_{b\beta}\, U^*_{d\delta}, \end{aligned}$$

(14 – 3) = 11 parameters

Higgs-family (HF) symmetries

$$\Phi_a \rightarrow \Phi_a^S = S_{ab}\Phi_b,$$

$$\begin{aligned} Y_{ab} &= S_{a\alpha}\, Y_{\alpha\beta}\, S_{b\beta}^*, \\ Z_{ab,cd} &= S_{a\alpha}\, S_{c\gamma}\, Z_{\alpha\beta,\gamma\delta}\, S_{b\beta}^*\, S_{d\delta}^*. \end{aligned}$$

Example:

$$Z_2: \qquad \Phi_1 \rightarrow \Phi_1, \qquad \Phi_2 \rightarrow -\Phi_2,$$

$$\begin{aligned} V_H &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right] \\ &+ \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left[\tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{H.c.} \right], \end{aligned}$$

Higgs-family (HF) symmetries and basis transformations

$$\Phi_1 = \frac{1}{\sqrt{2}}\left(\Phi_1' + \Phi_2'\right), \qquad \Phi_2 = \frac{1}{\sqrt{2}}\left(\Phi_1' - \Phi_2'\right).$$

==>

$$\frac{1}{\sqrt{2}}\left(\Phi_1' + \Phi_2'\right) \rightarrow \frac{1}{\sqrt{2}}\left(\Phi_1' + \Phi_2'\right), \qquad \frac{1}{\sqrt{2}}\left(\Phi_1' - \Phi_2'\right) \rightarrow -\frac{1}{\sqrt{2}}\left(\Phi_1' - \Phi_2'\right),$$

$$\Pi_2 : \qquad \Phi_1' \leftrightarrow \Phi_2',$$

Real

$$V_H = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right]$$
$$+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left[\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{H.c.}\right],$$

Real

$\lambda_6 = \lambda_7^*$

Higgs-family (HF) symmetries and basis transformations

symmetry	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
Z_2			0						0	0
Π_2		m_{11}^2	real		λ_1			real		λ_6^*

- These two models are the same but viewed in two different basis

- Obviously, they make the same physical predictions; we say that they are in the same class

Higgs-family (HF) symmetries and basis transformations

The symmetry

$$\Phi_a \longrightarrow \Phi_a^S = S_{ab}\Phi_b,$$

Under the basis change

$$\Phi'_a = U_{a\alpha}\Phi_\alpha$$

Transforms into

$$S' = U S U^\dagger$$

==>

$$S' = \begin{pmatrix} e^{-i\theta_1} & 0 \\ 0 & e^{i\theta_1} \end{pmatrix}$$

The usual CP transformation

$$\Phi_a(t, \vec{x}) \longrightarrow \Phi_a^{\mathrm{CP}}(t, \vec{x}) = \Phi_a^*(t, -\vec{x}),$$

$$\begin{aligned} (\Phi_1)^{\mathrm{CP}} &= (\Phi_1)^*\,, \\ (\Phi_2)^{\mathrm{CP}} &= (\Phi_2)^*\,. \end{aligned}$$

CP and basis transformations: General CP Transformations (GCP)

$$\Phi_1 = \frac{1}{\sqrt{2}}\,\Phi_1' + \frac{1}{\sqrt{2}}\,e^{i\pi/4}\,\Phi_2',$$
$$\Phi_2 = -\frac{1}{\sqrt{2}}\,e^{-i\pi/4}\,\Phi_1' + \frac{1}{\sqrt{2}}\,\Phi_2'.$$

$$\frac{1}{\sqrt{2}}\,(\Phi_1')^{\rm CP} + \frac{1}{\sqrt{2}}\,e^{i\pi/4}\,(\Phi_2')^{\rm CP} = \frac{1}{\sqrt{2}}\,(\Phi_1')^* + \frac{1}{\sqrt{2}}\,e^{-i\pi/4}\,(\Phi_2')^*$$
$$-\frac{1}{\sqrt{2}}\,e^{-i\pi/4}\,(\Phi_1')^{\rm CP} + \frac{1}{\sqrt{2}}\,(\Phi_2')^{\rm CP} = -\frac{1}{\sqrt{2}}\,e^{i\pi/4}\,(\Phi_1')^* + \frac{1}{\sqrt{2}}\,(\Phi_2')^*,$$

$$(\Phi_1')^{\rm CP} = \frac{1+i}{2}\,(\Phi_1')^* - \frac{i}{\sqrt{2}}\,(\Phi_2')^*,$$
$$(\Phi_2')^{\rm CP} = -\frac{i}{\sqrt{2}}\,(\Phi_1')^* + \frac{1-i}{2}\,(\Phi_2')^*.$$

Lee & Wick, PR 148, 1385 (1966)

This is NOT the usual type of CP transformation

CP and basis transformations: General CP Transformations (GCP)

We MUST consider GCP transformations

$$\Phi_a \quad \rightarrow \quad \Phi_a^{\mathrm{GCP}} = X_{a\alpha} \Phi_\alpha^*$$

Under the basis change

$$\Phi'_a \; = \; U_{a\alpha} \Phi_\alpha$$

The GCP transformation is changed according to:

$$X' = U X U^T.$$

==>

$$X' = U X U^T = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\boxed{0 \leq \theta \leq \pi/2}$$

Ecker, Grimus & Neufeld JPA 20, L807 (1987)

How many classes of symmetry-constrained potentials are there?

Invariance under some

$$\Phi_a \to S_{ab} \Phi_b,$$

and/or invariance under some

$$\Phi_a \to X_{ab} \Phi_b^*,$$

The 6 types of THDM scalar potentials

symmetry	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	$\mathbf{n}_{\text{parameters}}$
Z_2			0						0	0	**7**
$U(1)$			0					0	0	0	**6**
$U(2)$		m_{11}^2	0		λ_1		$\lambda_1 - \lambda_3$	0	0	0	**3**
CP1			real					real	real	real	**9**
CP2		m_{11}^2	0		λ_1					$-\lambda_6$	**5**
CP3		m_{11}^2	0		λ_1			$\lambda_1 - \lambda_3 - \lambda_4$ (real)	0	0	**4**

Ivanov, PRD 77, 015017 (2008)
Ferreira, Haber & JPS, PRD 79, 116004 (2009)

$$CP1: \qquad X = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix},$$

$$CP2: \qquad X = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix},$$

$$CP3: \qquad X = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$Z_2: \qquad S = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

$$U(1): \qquad S = \begin{pmatrix} e^{i\alpha} & 0 \\ 0 & e^{-i\alpha} \end{pmatrix}_{\alpha \neq \pi/2}$$

Extending GCP into the Yukawa terms

Yukawa Lagrangian

$$-\mathcal{L}_Y = \bar{q}_L(\Gamma_1\Phi_1 + \Gamma_2\Phi_2)n_R + \bar{q}_L(\Delta_1\tilde{\Phi}_1 + \Delta_2\tilde{\Phi}_2)p_R + \text{H.c.},$$

GCP transformations for fermions

$$\begin{aligned} q_L &\to X_\alpha \gamma^0 C q_L^*, \\ n_R &\to X_\beta \gamma^0 C n_R^*, \\ p_R &\to X_\gamma \gamma^0 C p_R^*, \end{aligned}$$

Use $X' = U X U^T$ and Ecker, Grimus, Neufeld to write:

$$X_\alpha = \left[\begin{array}{cc|c} c_\alpha & s_\alpha & 0 \\ -s_\alpha & c_\alpha & 0 \\ \hline 0 & 0 & 1 \end{array}\right],$$

Block structure

where $0 \leq \alpha \leq \pi/2$, and similarly for X_β and X_γ.

Extending GCP into the Yukawa terms

Forcing this GCP onto the Yukawa Lagrangian gives:

$$X_\alpha \Gamma_1^* - (c_\theta \Gamma_1 - s_\theta \Gamma_2) X_\beta = 0,$$
$$X_\alpha \Gamma_2^* - (s_\theta \Gamma_1 + c_\theta \Gamma_2) X_\beta = 0.$$

*** This gives us**

2 equations/matrices X 9 entries X 2 complex

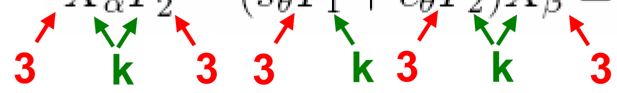
= 36 equations in 36 unkowns

*** Block structure means that we can separate problem into mn, m3, 3n, and 33 blocks (m,n=1,2).**

Extending GCP into the Yukawa terms

Simplest block is 33:

$$X_\alpha \Gamma_1^* - (c_\theta \Gamma_1 - s_\theta \Gamma_2) X_\beta = 0,$$
$$X_\alpha \Gamma_2^* - (s_\theta \Gamma_1 + c_\theta \Gamma_2) X_\beta = 0.$$



$$(\Gamma_1)^*_{33} - c_\theta (\Gamma_1)_{33} + s_\theta (\Gamma_2)_{33} = 0,$$
$$(\Gamma_2)^*_{33} - s_\theta (\Gamma_1)_{33} - c_\theta (\Gamma_2)_{33} = 0.$$

$$\begin{bmatrix} 1 - c_\theta & s_\theta \\ -s_\theta & 1 - c_\theta \end{bmatrix} \begin{bmatrix} \mathrm{Re}\,(\Gamma_1)_{33} \\ \mathrm{Re}\,(\Gamma_2)_{33} \end{bmatrix} = 0, \qquad \det = 2(1 - c_\theta),$$

$$\begin{bmatrix} 1 + c_\theta & -s_\theta \\ s_\theta & 1 + c_\theta \end{bmatrix} \begin{bmatrix} \mathrm{Im}\,(\Gamma_1)_{33} \\ \mathrm{Im}\,(\Gamma_2)_{33} \end{bmatrix} = 0. \qquad \det = 2(1 + c_\theta) \neq 0$$

Extending GCP into the Yukawa terms

Conclusions:

CP2: $\theta = \pi/2$

Γ_a matrix element	component	condition for vanishing determinant
33	Im	impossible
	Re	$\theta = 0$
13, 23	Im	$\alpha = \theta = \pi/2$
	Re	$\alpha = \theta$
31, 32	Im	$\beta = \theta = \pi/2$
	Re	$\beta = \theta$
11, 12, 21, 22	Im	$\theta = \pi - \alpha - \beta$
	Re	$\theta = \alpha + \beta$ or $\theta = \alpha - \beta$ or $\theta = \beta - \alpha$

$\Gamma_{1_{33}} = \Gamma_{2_{33}} = 0$

Block vanishes if $\alpha \neq \theta = \pi/2$

Block vanishes if $\beta \neq \theta = \pi/2$

Block vanishes if $\alpha = \beta = \theta = \pi/2$

==> All $\theta = \pi/2$ cases imply vanishing determinant

==> one zero down-type quark mass (& up-type & charged lepton)

==> We cannot extend CP2 to the quark sector

The single surviving model

* Perform a similar analysis for CP3 ($0 < \theta < \pi/2$)

==> There is one single way to extend CP3 to the quark sector consistent with non-vanishing quark masses!!

==> One must have $\alpha = \beta = \theta = \pi/3$ and

$$\Gamma_1 \rightarrow \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & -a_{11} & a_{23} \\ a_{31} & a_{32} & 0 \end{bmatrix},$$

$$\Gamma_2 \rightarrow \begin{bmatrix} a_{12} & -a_{11} & -a_{23} \\ -a_{11} & -a_{12} & a_{13} \\ -a_{32} & a_{31} & 0 \end{bmatrix},$$

6 real parameters

Fit to experiment

- **The model is CP conserving.**
  ==> There is also no exact CP3 model
  CPV is accommodated by breaking CP3 softly (later...)

- **With the CPV vacuum phase there are in principle 15 parameters**
  - 6 real parameters from down Yukawa
  - 6 real parameters from up Yukawa
  - 2 vevs
  - 1 vacuum phase

- **Fit to 11 observables**
  - 3 + 3 quark masses
  - 3 + 1 CKM parameters
  - v^2

Fit to experiment

$$a_{11} = 4.6927 \times 10^{-6}, \quad a_{12} = -5.9799 \times 10^{-4},$$
$$a_{13} = -2.32 \times 10^{-2}, \quad a_{23} = -6.6 \times 10^{-3},$$
$$a_{31} = -8.815 \times 10^{-5}, \quad a_{32} = 5.1193 \times 10^{-6},$$

$$v_1 = 173.944, \quad v_2 \cos\delta = -0.8467 \quad v_2 \sin\delta = -0.9565$$

$$b_{11} = 7.3 \times 10^{-3}, \quad b_{12} = 7.6445 \times 10^{-5},$$
$$b_{13} = 9.578 \times 10^{-1}, \quad b_{23} = 2.325 \times 10^{-1},$$
$$b_{31} = 1.3446 \times 10^{-4}, \quad b_{32} = 5.9491 \times 10^{-4},$$

==>

$$m_d = 0.00298, \quad m_s = 0.10511, \quad m_b = 4.19701,$$
$$m_u = 0.00200, \quad m_c = 1.27439, \quad m_t = 171.451,$$

$$|V| = \begin{bmatrix} 0.97430 & 0.22521 & 0.00339 \\ 0.22516 & 0.97348 & 0.04039 \\ 0.00579 & 0.04011 & 0.99918 \end{bmatrix}.$$

$$0.00874^{+0.00026}_{-0.00037}$$ **PDG (2008)**

==> Good agreement with PDG
Except V_{td}

What about FCNC?

- The model does have FCNC

- Maybe suppressed by making scalar masses large enough and/or couplings small enough
  - 15 parameters for 11 observables

- Otherwise, redo the analysis leading to CKM extraction

CP Violation in the 6 types of THDM scalar potentials

symmetry	exact		softly-broken	
	explicit CPV	spontaneous CPV	explicit CPV	spontaneous CPV
Z_2	–	–	Yes	Yes
$U(1)$	–	–	–	–
$U(2)$	–	–	–	–
CP1	–	Yes	Yes	Yes
CP2	–	–	Yes	Yes
CP3	–	–	–	–

TDLee, PRD 8, 1226 (1973)
Branco & Rebelo, PLB 160, 117 (1985)
Ferreira, Maniatis, Nachtmann & JPS, JHEP08 (2010) 125

The lagrangian does not have explicit CPV

$$
\begin{aligned}
V_H &= m^2 \left[\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2\right] \\
&+ \tfrac{1}{2}\lambda_1 \left[(\Phi_1^\dagger \Phi_1)^2 + (\Phi_2^\dagger \Phi_2)^2\right] + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&+ \tfrac{1}{2}(\lambda_1 - \lambda_3 - \lambda_4) \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2\right] \\
&+ \Delta m^2 \left[\Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2\right] - m_{12}^2 \left[\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right],
\end{aligned}
$$

(first three lines:) **CP3**

(last line:) $\longrightarrow$ **soft-breaking of CP3**

- m_{12}^2 **(hence, V_H) kept real by imposing also CP1**
- **all Yukawa couplings real**

==> Lagrangian preserves CP

==> This is not SM-like CPV

The scalar sector of the model does not have spontaneous CPV

Proofs:

- **Bilinears**
  Ferreira, Maniatis, Nachtmann & JPS, JHEP08 (2010) 125

- **Calculate the basis invariant signals of CPV after SEwkSB – J_1, J_2, and J_3 – of**
  Lavoura & JPS, PRD 50, 4619 (1994)
  Botella & JPS, PRD 51, 3870 (1995)

- **Go to the Higgs basis and count independent phases**
  Ferreira & JPS, arXiv:1001.0574, EPJC (in print)

The Higgs basis

Do

$$\Phi_a = U_{ab} H_b \qquad U^\dagger = \frac{1}{v} \left[\begin{array}{cc} v_1 & v_2 e^{-i\delta} \\ v_2 & -v_1 e^{-i\delta} \end{array} \right]$$

As a result

$$H_1 = \left[\begin{array}{c} G^+ \\ (v + H^0 + i G^0)/\sqrt{2} \end{array} \right], \quad H_2 = \left[\begin{array}{c} H^+ \\ (R + i I)/\sqrt{2} \end{array} \right]$$

arbitrary phase

vevless

The Higgs basis

==>

$$V_H = \bar{m}_{11}^2 H_1^\dagger H_1 + \bar{m}_{22}^2 H_2^\dagger H_2 - \left[\bar{m}_{12}^2 H_1^\dagger H_2 + \text{H.c.}\right] + \tfrac{1}{2}\bar{\lambda}_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2}\bar{\lambda}_2 (H_2^\dagger H_2)^2$$
$$+ \bar{\lambda}_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \bar{\lambda}_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left[\tfrac{1}{2}\bar{\lambda}_5 (H_1^\dagger H_2)^2 + \bar{\lambda}_6 (H_1^\dagger H_1)(H_1^\dagger H_2)\right.$$
$$\left. + \bar{\lambda}_7 (H_2^\dagger H_2)(H_1^\dagger H_2) + \text{H.c.}\right].$$

Stationarity conditions ==> $2\bar{m}_{12}^2 = \bar{\lambda}_6 v^2$

Arbitrary phase of H_2

==> Signals of CPV are: $\text{Im}(\bar{\lambda}_6 \, \bar{\lambda}_7^*)$, $\text{Im}(\bar{\lambda}_5^* \, \bar{\lambda}_6^2)$, and $\text{Im}(\bar{\lambda}_5^* \, \bar{\lambda}_7^2)$

Lavoura & JPS, PRD 50, 4619 (1994)

The scalar sector of the model does not have spontaneous CPV

Transforming the coefficients of the scalar potential into the Higgs basis, we get

$$-\bar{\lambda}_7 = \bar{\lambda}_6 = \frac{2}{v^4} v_1 v_2 (\lambda_1 - \lambda_3 - \lambda_4) \sin\delta \ \eta$$

$$\bar{\lambda}_5 = -\frac{1}{v^4} (\lambda_1 - \lambda_3 - \lambda_4) \ \eta^2$$

$$\eta = -i \left(v_1^2 e^{i\delta} + v_2^2 e^{-i\delta} \right).$$

==> The scalar sector is CP conserving, even after spontaneous electroweak symmetry breaking

==> This is not the usual type of spontaneous CPV

The model does have CPV

Define

$$\sqrt{2}\,\Gamma_d = v_1\Gamma_1 + v_2 e^{i\delta}\Gamma_2, \qquad H_d = \Gamma_d(\Gamma_d)^\dagger,$$
$$\sqrt{2}\,\Delta_u = v_1\Delta_1 + v_2 e^{-i\delta}\Delta_2. \qquad H_u = \Delta_u(\Delta_u)^\dagger.$$

Basis invariant source of CPV in W interactions is

$$\begin{aligned} J &= \mathrm{Tr}[H_u, H_d]^3 = 6i(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \\ &\times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)\mathrm{Im}\,(V_{us}V_{cb}V_{ub}^*V_{cs}^*)\,. \end{aligned}$$

$\propto \sin(\delta)$ **Bernabéu, Branco & Gronau, PL 169B, 243 (1986)**

==> The model does have a weird spontaneous CPV

*** scalar sector does the deed**

spontaneously break electroweak symmetry

*** quark sector pays the price**

violates CP

Open questions

- **Are there FCNC?**
  - **Yes.** — 11 — 0 — Lavoura
  - **FCNC couplings depend on only 15-11=4 new parameters** (arrows: 11 → 11, 4 → 0)
  - **masses of scalars depend on only 2 (3) more**

==> FCNC are <u>very</u> constrained

Open questions

- **After Lavoura**
  - **Fitting [quark masses] allows for large scalar masses**
  - **BUT, fitting [quark masses + CKM] forces one small scalar mass**

- **This problem goes away if you take a complex soft-CP3 breaking term**
  - **Good fits to four of**
    - **KK mixing**
    - ε_K
    - **BB mixing**
    - **BsBs mixing**
    - **sin(2β)**

Open questions

- **Are there other models with this new type of spontaneous CPV?**
  - **we have built 3HDM like this**
  - **BUT**
    - **they are THDM-like (third vev vanishes)**
    - **general 3HDM do not seem to exhibit this new type of CPV**

Conclusions

- **It is important to consider Generalized CP transformations/symmetries**
- **The CP2 symmetry cannot be extended to the Yukawa sector in a way consistent with non-zero quark masses**
- **The exact CP3 symmetry cannot be extended to the Yukawa sector in a way consistent with non-zero quark masses and CPV**

Conclusions

- **There is one single softly-broken CP3-symmetric model which can be extended to the Yukawa sector in a way consistent with non-zero quark masses and CPV**

- **The model is very constrained and may be in trouble (in progress...)**
  - **If it survives de assault, fine**
  - **If it does not, we will have proved that there is <u>no</u> possible extension of GCP into the Yukawa sector**

Conclusions

- **In any case:**

  There is a new type of spontaneous CPV.

  Search is on for other models of this type.

END