2HD U PRIMJENAMA

- **OPĆI CP-SIMETRIČNI 2HDM**
- **KOMPLEKSNI C2HDM S CP NARUŠENJEM prema Fontes et al./1506.06755**

Motivacija za dodatni HD

- U supersimetriji – vidjeti MSSM
- Uz Peccei-Quinninu simetriju
- U modelima bariogeneze
- U modelima tamne tvari – detaljnije od inertnog dubleta do skotogeničkih modela

- **Uz P-Q simetriju**

R. D. Peccei and H. R. Quinn, *"CP Conservation in the Presence of Instantons,"* Phys. Rev. Lett. **38**, 1440 (1977).

R. D. Peccei and H. R. Quinn, *"Constraints Imposed by CP Conservation in the Presence of*

- **U modelima bariogeneze**

N. Turok and J. Zadrozny, *"Electroweak baryogenesis in the two doublet model,"* Nucl. Phys. B **358**, 471 (1991).

Podvostručenje dubleta (2HDM)-“alignment” u parametrizaciji

$$\Phi_i = \begin{pmatrix} w_i^+(x) \\ \dfrac{v_i + h_i(x) + iz_i(x)}{\sqrt{2}} \end{pmatrix}, \qquad i = 1,2 \qquad \tan\beta = \frac{v_2}{v_1}$$

- **Svođenje na poravnatu, SM-granicu, rot. β**

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \qquad \begin{pmatrix} H^0 \\ R \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

The physical scalar h is related to H^0

$$\sin(\beta - \alpha) \approx 1\,,$$

$$h = \sin(\beta - \alpha) H^0 + \cos(\beta - \alpha) R\,.$$

$$\beta - \alpha = \tfrac{\pi}{2}$$

Najopćenitiji (ne-SuSy) 2HDM uz potencijal koji čuva CP

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,(G^+ \cos\beta - H^+ \sin\beta) \\ v_1 - h\sin\alpha + H\cos\alpha + \mathrm{i}\,(G\cos\beta - A\sin\beta) \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,(G^+ \sin\beta + H^+ \cos\beta) \\ v_2 + h\cos\alpha + H\sin\alpha + \mathrm{i}\,(G\sin\beta + A\cos\beta) \end{pmatrix}$$

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

- **Izbjegavanje FCNC uz "natural flavor cons"**

impose a Z_2 symmetry so that each type of fermion only couples to one of the doublets (forcing $\lambda_6 = \lambda_7 = 0$)

	Type-I	Type-II	Type-X	Type-Y
Φ_1	-	$d,\ e$	e	d
Φ_2	$u,\ d,\ e$	u	$u,\ d$	$u,\ e$
(ξ_u, ξ_d, ξ_e)	$(\cot\beta, \cot\beta, \cot\beta)$	$(\cot\beta, -\tan\beta, -\tan\beta)$	$(\cot\beta, \cot\beta, -\tan\beta)$	$(\cot\beta, -\tan\beta, \cot\beta)$

- Type I: All quarks and leptons couple only to the doublet ϕ_2
- Type II: ϕ_2 couples to the up-type quarks and ϕ_1 couples to down-type quarks and charged leptons
- Type X or lepton specific: All quarks couple to ϕ_2, while ϕ_1 couples to the charged leptons
- Type Y or flipped: Up-type quarks and charged leptons couple to ϕ_2 and all down-type quarks couple to ϕ_1

$$\mathcal{L}_Y = \bar{Q}_L \frac{M_d}{v}(\Phi + \sqrt{2}\xi_d \Psi) d_R + \bar{Q}_L \frac{M_u}{v}(i\sigma_2 \Phi^* + \sqrt{2}\xi_u (i\sigma_2)\Psi^*) u_R + \bar{L}_L \frac{M_e}{v}(\Phi + \sqrt{2}\xi_e \Psi) e_R + \text{h.c.}$$

Modifikacija Higgsovih vezanja u nekoliko poravnatih modela

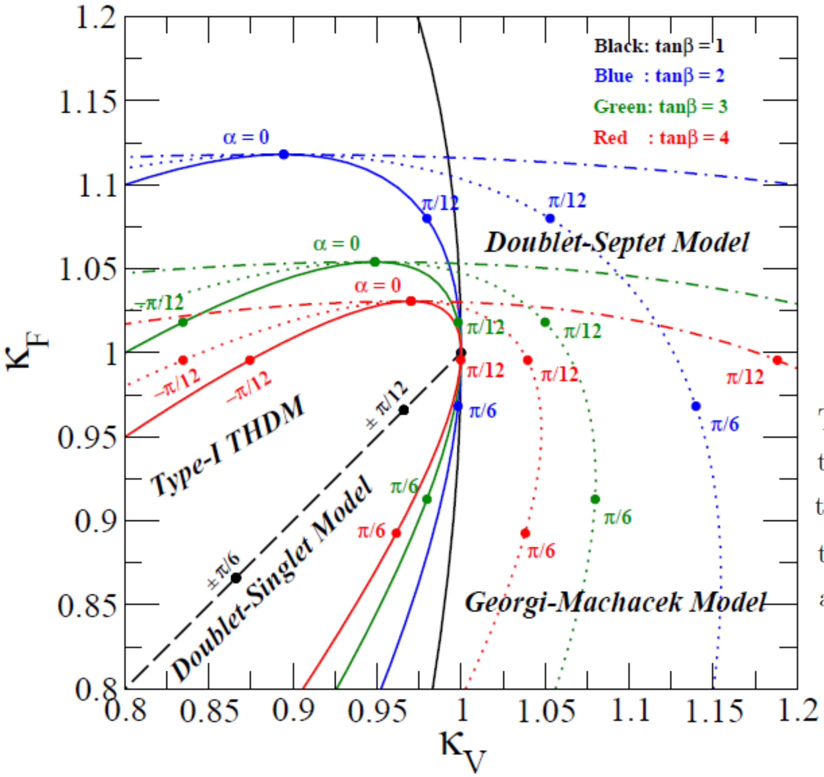
- Devijacije izražene "faktorima skaliranja"

$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\rm SM}}, \quad \kappa_f = \frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{\rm SM}}$$

Na temelju postojećih mjerenja

$$\kappa_V = 1.15 \pm 0.08, \quad \kappa_f = 0.99^{+0.08}_{-0.15}, \quad \text{ATLAS [2]},$$
$$\kappa_V = 1.01 \pm 0.07, \quad \kappa_f = 0.87^{+0.14}_{-0.13}, \quad \text{CMS [4]},$$

where universal scaling factors, i.e., $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$ and $\kappa_V = \kappa_W = \kappa_Z$ are assumed

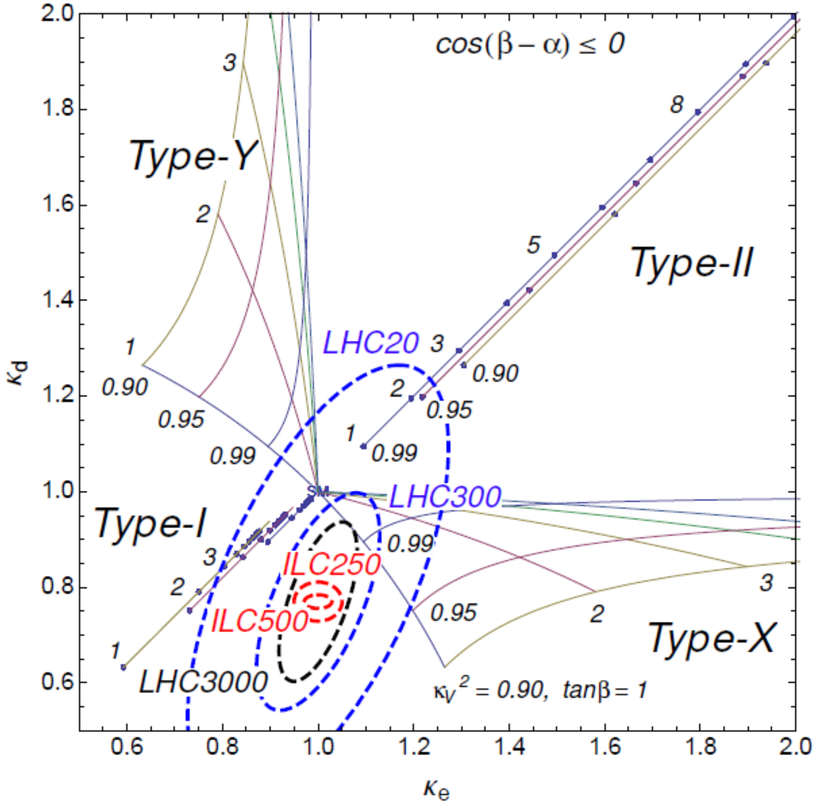


The scaling factors κ_f and κ_V for each value of β and α in the Doublet-Singlet model (dashed), the Type-I THDM (solid), the GM model (dotted), and the Doublet-Septet model (dash-dotted) [1]

[1] S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, Phys. Rev. D **90**, no. 7, 075001 (2014)

Simple extended Higgs sectors with $\rho_{\text{tree}} = 1$ and without tree level FCNCs

Models	Doublet-Singlet Model	THDMs	GM Model	Doublet-Septet Model
Scalar field contents	$\Phi + \varphi(0,0)$	$\Phi + \varphi(1/2,1/2)$	$\Phi + \varphi(1,0) + \varphi(1,1)$	$\Phi + \varphi(3,2)$



The flavor universal scaling factors κ_e and κ_d for each value of β and α in the four THDMs with different types

we can distinguish non-minimal Higgs sectors by *fingerprinting* the Higgs boson couplings, namely, comparing the predicted Higgs boson couplings and precisely measured values at future collider experiments

2HDM s globalnom U(1)

- Poopćenje Z_2 na globalnu simetriju U(1) (Biswas-Lahiri/arXiv:1412.6187,realni λ_i)

$$
\begin{aligned}
V = {} & \lambda_1 \left(|\Phi_1|^2 - \frac{v_1^2}{2} \right)^2 + \lambda_2 \left(|\Phi_2|^2 - \frac{v_2^2}{2} \right)^2 \\
& + \lambda_3 \left(|\Phi_1|^2 + |\Phi_2|^2 - \frac{v_1^2 + v_2^2}{2} \right)^2 \\
& + \lambda_4 \left(|\Phi_1|^2 |\Phi_2|^2 - |\Phi_1^\dagger \Phi_2|^2 \right) \\
& + \lambda_5 \left| \Phi_1^\dagger \Phi_2 - \frac{v_1 v_2}{2} \right|^2 ,
\end{aligned}
$$

invariant under the symmetry $\Phi_1 \to e^{i\theta} \Phi_1 \, , \Phi_2 \to \Phi_2 \, ,$

a soft breaking term $\lambda_5 v_1 v_2 \Re(\Phi_1^\dagger \Phi_2) \, .$

Granica "stabilnog poravnanja"

The general 2HDM potential with Z_2 symmetry under which $\phi_1 \to \phi_1$ and $\phi_2 \to -\phi_2$

$$V_{2\mathrm{HDM}} = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - \left(m_{12}^2\phi_1^\dagger\phi_2 + \mathrm{h.c.}\right) + \frac{\lambda_1}{2}\left(\phi_1^\dagger\phi_1\right)^2 + \frac{\lambda_2}{2}\left(\phi_2^\dagger\phi_2\right)^2$$
$$+\lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) + \left\{\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \mathrm{h.c.}\right\},$$

where the term proportional to m_{12}^2 breaks the Z_2 symmetry softly.

- **8 parametra: dva $v_{1,2}$ i šest β_i**

$$V_{2\mathrm{HDM}} = \beta_1\left(\phi_1^\dagger\phi_1 - \frac{v_1^2}{2}\right)^2 + \beta_2\left(\phi_2^\dagger\phi_2 - \frac{v_2^2}{2}\right)^2 + \beta_3\left(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 - \frac{v_1^2+v_2^2}{2}\right)^2$$
$$+\beta_4\left\{(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) - (\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)\right\} + \beta_5\left(\mathrm{Re}\,\phi_1^\dagger\phi_2 - \frac{v_1v_2}{2}\right)^2 + \beta_6\left(\mathrm{Im}\,\phi_1^\dagger\phi_2\right)^2$$

β_5 plays the role of the soft breaking parameter

in the limit $\beta_5 = \beta_6$ the symmetry of the 2HDM potential is enhanced from softly broken Z_2 to softly broken $U(1)$ under which $\phi_1 \to \phi_1$ and $\phi_2 \to e^{i\theta}\phi_2$

Neinertni slučaj – veza parametara za neiščezavajući tan β

$$m_{11}^2 = -(\beta_1 v_1^2 + \beta_3 v^2) \; ; \qquad \lambda_1 = 2(\beta_1 + \beta_3) \; ;$$
$$m_{22}^2 = -(\beta_2 v_2^2 + \beta_3 v^2) \; ; \qquad \lambda_2 = 2(\beta_2 + \beta_3) \; ;$$
$$m_{12}^2 = \frac{\beta_5}{2} v_1 v_2 \; ; \qquad \lambda_3 = (2\beta_3 + \beta_4) \; ;$$
$$\lambda_4 = \frac{\beta_5 + \beta_6}{2} - \beta_4 \; ; \qquad \lambda_5 = \frac{\beta_5 - \beta_6}{2} \; .$$

- **Praćenje mekog loma simetrije:**

the relation between m_{12}^2 and β_5 $\quad m_{12}^2 = \frac{\beta_5}{2} v_1 v_2$
suggests that β_5 is a better parameter
for tracking the effect of soft breaking

Neinertni slučaj – veza parametara za neiščezavajući tan β

$$m_{11}^2 = -(\beta_1 v_1^2 + \beta_3 v^2) \; ; \qquad \lambda_1 = 2(\beta_1 + \beta_3) \; ;$$
$$m_{22}^2 = -(\beta_2 v_2^2 + \beta_3 v^2) \; ; \qquad \lambda_2 = 2(\beta_2 + \beta_3) \; ;$$
$$m_{12}^2 = \frac{\beta_5}{2} v_1 v_2 \; ; \qquad \lambda_3 = (2\beta_3 + \beta_4) \; ;$$
$$\lambda_4 = \frac{\beta_5 + \beta_6}{2} - \beta_4 \; ; \qquad \lambda_5 = \frac{\beta_5 - \beta_6}{2} \; .$$

- Kut miješanja u CP-parnom sektoru (α) i četiri mase skalara

$$\tan 2\alpha = \frac{2(\beta_3 + \frac{\beta_5}{4}) v_1 v_2}{\beta_1 v_1^2 - \beta_2 v_2^2 + (\beta_3 + \frac{\beta_5}{4})(v_1^2 - v_2^2)}$$

$$m_h, m_H, m_A \text{ and } m_{H^+}$$

- β-parametri (osim β5) mogu se izraziti s četiri mase fizikalnih skalara i kutom α

$$
\begin{aligned}
\beta_1 &= \frac{1}{2v^2 c_\beta^2}\left[m_H^2 c_\alpha^2 + m_h^2 s_\alpha^2 - \frac{s_\alpha c_\alpha}{\tan\beta}\left(m_H^2 - m_h^2\right)\right] - \frac{\beta_5}{4}\left(\tan^2\beta - 1\right), \\
\beta_2 &= \frac{1}{2v^2 s_\beta^2}\left[m_h^2 c_\alpha^2 + m_H^2 s_\alpha^2 - s_\alpha c_\alpha \tan\beta\left(m_H^2 - m_h^2\right)\right] - \frac{\beta_5}{4}\left(\cot^2\beta - 1\right), \\
\beta_3 &= \frac{1}{2v^2}\frac{s_\alpha c_\alpha}{s_\beta c_\beta}\left(m_H^2 - m_h^2\right) - \frac{\beta_5}{4}, \\
\beta_4 &= \frac{2}{v^2} m_{H+}^2, \\
\beta_6 &= \frac{2}{v^2} m_A^2 .
\end{aligned}
$$

U granici poravnanja $\beta - \alpha = \frac{\pi}{2}$

h will have the exactly SM-like tree-level couplings , $m_h \approx 125$ GeV

five unknown parameters (m_H, m_A, m_{H^+}, β_5 and $\tan\beta$) will be constrained from the requirement of high scale stability of the 2HDM potential

- **Teor. granice u početnoj parametrizaciji**

  the necessary and sufficient conditions for the potential to be bounded from below read [22, 23]

$$\lambda_1 > 0,$$
$$\lambda_2 > 0,$$
$$\lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0,$$
$$\lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1 \lambda_2} > 0$$

Eksperimentalna ograničenja

- Expt. granice iz fizike okusa (b->s γ)

- There is a very strong lower limit on m_{H^+}, for Type II models, $m_{H^+} > 300$ GeV [28, 29] from flavor data – hold for Type Y models too

for Type I and X models
we only consider the direct search limit $m_{H^+} > 80$ GeV [30].

Expt. granice iz parametara "nagnuća" (oblique)

- The oblique T-parameter can restrict the splitting between the heavy scalar masses. In the 2HDM alignment limit, the expression for the new physics contribution to the T-parameter $\Delta T = 0.05 \pm 0.12$

$$\Delta T = \frac{1}{16\pi \sin^2\theta_w M_W^2}\left[F(m_{H^+}^2, m_H^2) + F(m_{H^+}^2, m_A^2) - F(m_H^2, m_A^2)\right] ,$$

$$F(x,y) = \begin{cases} \frac{x+y}{2} - \frac{xy}{x-y}\ln\left(\frac{x}{y}\right) & \text{for } x \neq y\,, \\ 0 & \text{for } x = y\,. \end{cases}$$

$F(x,y)$ is symmetric under $x \leftrightarrow y$ and is sensitive only to the difference $|x-y|$

Thus $\Delta T = 0$ when either $m_{H^+} = m_H$ or $m_{H^+} = m_A$ – no constraints

if, for some reason, $m_H \approx m_A$ then ΔT severely restricts the splitting between charged and neutral scalar masses

C2HDM S CP NARUŠENJEM

- prema Fontes et al./1506.06755

has a softly broken Z_2 symmetry $\phi_1 \to \phi_1, \phi_2 \to -\phi_2$ and the scalar potential

$$
\begin{aligned}
V_H = {} & m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2\,\phi_1^\dagger\phi_2 - (m_{12}^2)^*\,\phi_2^\dagger\phi_1 \\
& + \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4\,(\phi_1^\dagger\phi_2)\,(\phi_2^\dagger\phi_1) \\
& + \frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \frac{\lambda_5^*}{2}(\phi_2^\dagger\phi_1)^2\,,
\end{aligned}
$$

all couplings except m_{12}^2 and λ_5 are real.

- **Da se dvije faze nebi istovremeno uklonile** we impose $\arg(\lambda_5) \neq 2\arg(m_{12}^2)$

By taking m_{12}^2 and λ_5 real we recover the corresponding CP-conserving 2HDM

The mass matrix of the neutral scalar particles with no definite CP is obtained via the rotation matrix

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

with $s_i = \sin\alpha_i$ and $c_i = \cos\alpha_i$ $(i = 1, 2, 3)$ and

$$-\pi/2 < \alpha_1 \leq \pi/2, \qquad -\pi/2 < \alpha_2 \leq \pi/2, \qquad -\pi/2 \leq \alpha_3 \leq \pi/2.$$

9 nezavisnih parametara u C2HDM – odabir za studij raspada higgsa u 1506.06755

$$v,\ \tan\beta,\ m_{H^\pm},\ \alpha_1,\ \alpha_2,\ \alpha_3,\ m_1,\ m_2,\ \text{and}\ \mathrm{Re}(m_{12}^2)$$

- U tom odabiru je masa težeg neutralnog skalara

$$m_3^2 = \frac{m_1^2\, R_{13}(R_{12}\tan\beta - R_{11}) + m_2^2\, R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

a parametarski prostor ograničen

to values which obey $m_3 > m_2$

Studij CP primjese stanju 126 GeV

- Prema Chen-Zhang/1503.01114

$$V(\phi_1,\phi_2) = -\frac{1}{2}\left[m_{11}^2(\phi_1^\dagger\phi_1) + \left(m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right) + m_{22}^2(\phi_2^\dagger\phi_2)\right]$$
$$+\frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)$$
$$+\frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1) + \lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_2) + \text{h.c.}\right] \; .$$

the imaginary parts of m_{12} and λ_5 lead to mixing in the neutral Higgs sector between H_1^0, H_2^0 and A^0, and that is the source of CP violation

9 fizikalnih parametara prema 1503.01114

- The scalar masses, m_{h_1}, m_{h_2}, m_{h_3} and $m_{H^\pm}$
- The neutral scalar mixing angles, α, α_b, α_c
- The ratio of vev's, $\tan\beta$
- One potential parameter, $\mathrm{Re}(m_{12}^2)$, or $\nu \equiv \mathrm{Re}(m_{12})^2/(v^2 \sin 2\beta)$

The ν parameter controls the decoupling limit, *i.e.*, when $\mathrm{Re}(m_{12})^2$ approaches infinity, the masses of h_2, h_3 and $H^\pm$ also go to infinity.

The imaginary part of λ_5, which is a source of CP violation

$$\mathrm{Im}\lambda_5 = \frac{2\cos\alpha_b}{v^2\sin\beta}\Big[(m_{h_2}^2 - m_{h_3}^2)\cos\alpha\sin\alpha_c\cos\alpha_c \\ +(m_{h_1}^2 - m_{h_2}^2\sin^2\alpha_c - m_{h_3}^2\cos^2\alpha_c)\sin\alpha\sin\alpha_b\Big]$$

in order for the 126 GeV Higgs boson to have CP violating couplings, the heavy Higgs states must not decouple

Type−I w. approximate Z_2: m_{h_2} =550GeV, m_{h_3} =600GeV, $m_{H^\pm}$ =620GeV, ν=1