Spontaneous CP breaking in S_3 flavored Higgs sector

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Outline

Motivation

- Studies have been started in the 70's, hoping to find global symmetry that explains the mass and mixing patterns.

  Pakvasa et al (1978); Derman and Tsao (1979);Yahalom (1984); Wyler (1979); A. Mondragón et al (1999); Kubo et al (2004); etc
- S_3 is the smallest flavour symmetry suggested by data.
- Previous works in the quarks and neutrinos sector.

  Kubo et al (2004); A. Mondragón et al (2007); F. Gonzalez (2012); etc
- Extending the concept of flavour to the Higgs sector by adding two more EW doublets.
- Without the symmetry $\rightarrow$ 54 real parameters in the potential.
- Low energy model.
- Testable model.
- Possibles sources from CP violation.

The potential of three-Higgs-doublets under the symmetry S_3

- The lagrangian of the Higgs sector under the symmetry S_3 is given as:

$$\mathcal{L}_\phi = (D_\mu H_s)^2 + (D_\mu H_1)^2 + (D_\mu H_2)^2 - V(H_1, H_2, H_s). \tag{1}$$

- The potential $V(H_1, H_2.H_s)$ more general for the three higgs doublet model invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y \times S_3$ is the following:

$$\begin{aligned} V \quad = \quad & \mu_1^2\left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \mu_0^2\left(H_s^\dagger H_s\right) + \frac{a}{2}\left(H_s^\dagger H_s\right)^2 + b\left(H_s^\dagger H_s\right)\left(H_1^\dagger H_1 + H_2^\dagger H_2\right) \\ & + \frac{c}{2}\left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 + \frac{d}{2}\left(H_1^\dagger H_2 - H_2^\dagger H_1\right)^2 + ef_{ijk}\left(\left(H_s^\dagger H_i\right)\left(H_j^\dagger H_k\right) + h.c.\right) \\ & + f\left\{\left(H_s^\dagger H_1\right)\left(H_1^\dagger H_s\right) + \left(H_s^\dagger H_2\right)\left(H_2^\dagger H_s\right)\right\} + \frac{g}{2}\left\{\left(H_1^\dagger H_1 - H_2^\dagger H_2\right)^2 + \left(H_1^\dagger H_2 + H_2^\dagger H_1\right)^2\right\} \\ & + \frac{h}{2}\left\{\left(H_s^\dagger H_1\right)\left(H_s^\dagger H_1\right) + \left(H_s^\dagger H_2\right)\left(H_s^\dagger H_2\right) + \left(H_1^\dagger H_s\right)\left(H_1^\dagger H_s\right) + \left(H_2^\dagger H_s\right)\left(H_2^\dagger H_s\right)\right\}. \end{aligned} \tag{2}$$

- The three Higgs doubles of $SU(2)$: H_1, H_2 and H_s can be writing in the following way:

$$H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_4 \\ \phi_7 + i\phi_{10}\end{pmatrix} \quad , \quad H_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_2 + i\phi_5 \\ \phi_8 + i\phi_{11}\end{pmatrix} \tag{3}$$

$$H_s = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_3 + i\phi_6 \\ \phi_9 + i\phi_{12}\end{pmatrix} \quad .$$

Kubo et al (2004); Felix-Beltrán, Rodríguez-Jáuregui, M.M (2009), Das and Dey (2014), Barradas et al (2014), Costa, Ogreid, Osland and Rebelo (2016), etc

- The CP conserving case, the vacuum expectation values (vev) of the Higgs doublets are taken as real values.

$$\phi_7 = v_1, \phi_8 = v_2, \phi_9 = v_3, \phi_i = 0, \quad i \neq 7, 8, 9, \tag{4}$$

- The CP breaking minimum (CPB)

$$\langle H_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i + i\gamma_i \end{pmatrix} \quad i = 1, 2, s, \tag{5}$$

- where $\gamma_i \in \mathrm{Re}$. Then, CPB is at

$$\phi_7 = v_1,\ \phi_8 = v_2,\ \phi_9 = v_3,\ \phi_{10} = \gamma_1,\ \phi_{11} = \gamma_2,\ \phi_{12} = \gamma_3, \qquad \text{and other cases} \qquad \phi_i = 0,$$

- which should satisfy the constraint

$$v = \left(v_1^2 + v_2^2 + v_3^2 + \gamma_1^2 + \gamma_2^2 + \gamma_3^2\right)^{1/2}. \tag{7}$$

- Our analysis it is going to take $\gamma_3 \neq 0$ and the others equal to zero.
- So it should satisfy the constraint

$$v = \left(v_1^2 + v_2^2 + v_3^2 + \gamma_3^2\right)^{1/2}. \tag{8}$$

- The condition of the minimum fixes :

$$
\begin{aligned}
v_1^2 &= 3v_2^2, \quad \frac{h}{e} = -\frac{v_2}{v_3}, \\
\mu_1^2 &= \frac{1}{\sqrt{2}}\left(-\gamma_3^2 k_1 - 4k_2 v_2^2 - (b+f-5h)v_3^2\right), \\
\mu_0^2 &= -2k_1 v_2^2 - \frac{a}{2}(\gamma_3^2 + v_3^2).
\end{aligned} \tag{9}
$$

- where $k_1 = b + f - h, \quad k_2 = c + g$

Felix-Beltrán, Rodríguez-Jáuregui, M.M; Costa et al

- The minimum of potential can be parameterized in spherical coordinates, three angles and v.

$$v_1 = v\cos\varphi\sin\theta\sin\phi, \quad v_2 = v\sin\varphi\sin\theta\sin\phi, \quad v_3 = v\cos\theta\sin\phi \quad \gamma_3 = v\cos\phi.$$

$\tan\varphi = \pm\frac{1}{\sqrt{3}}$, which means $\varphi = \pi/6$, therefore:

$$\tan\varphi = 1/\sqrt{3} \quad \Rightarrow \quad \sin\varphi = \frac{1}{2} \quad \& \quad \cos\varphi = \frac{\sqrt{3}}{2}. \tag{10}$$

- The properties Higgs and Goldstone bosons have been found after diagonalize the 12×12 matrix $(\mathcal{M}_H^2)_{ij} = \frac{1}{2}\frac{\partial^2 V}{\partial\phi_i \partial\phi_j}\Big|_{\text{CPBmin}}$. We have

$$\mathcal{M}_H^2 = \text{diag}\left(\mathbf{M}^2_{C,\gamma_3}, \mathbf{M}^2_{N,\gamma_3}\right) , \tag{11}$$

- with $\mathbf{M}^2_{C,\gamma_3}$ corresponding to the mass matrix of electrically charged Higgs bosons and $\mathbf{M}^2_{N,\gamma_3}$ to the neutral Higgs mass matrix, which are the 6×6 symmetric and Hermitian sub-matrices.
- The matrix that give us the general form for charged states are:

$$\mathbf{M}^2_{C,\gamma_3} = \begin{pmatrix} \mathbf{M}^2_{\mathbf{C}11}(\gamma_3) & \mathbf{M}^2_{\mathbf{C}12}(\gamma_3) \\ \mathbf{M}^2_{\mathbf{C}21}(\gamma_3) & \mathbf{M}^2_{\mathbf{C}22}(\gamma_3) \end{pmatrix} , \tag{12}$$

which should satisfy the constraint

$$\begin{aligned} \mathbf{M}^2_{\mathbf{C}22}(\gamma_3) &= \mathbf{M}^2_{\mathbf{C}11}(\gamma_3), \\ \mathbf{M}^2_{\mathbf{C}21}(\gamma_3) &= -\mathbf{M}^2_{\mathbf{C}12}(\gamma_3). \end{aligned} \tag{13}$$

- The matrix that give us the general form for neutral states are:

$$\mathbf{M}^2_{N,\gamma} = \begin{pmatrix} \mathbf{M^2_{N11}}(\gamma) & \mathbf{M^2_{N12}}(\gamma) \\ \mathbf{M^2_{N21}}(\gamma) & \mathbf{M^2_{N22}}(\gamma) \end{pmatrix}, \tag{14}$$

with

$$\begin{aligned} \mathbf{M^2_{N22}}(\gamma) &\neq \mathbf{M^2_{N11}}(\gamma), \\ \mathbf{M^2_{N21}}(\gamma) &= \mathbf{M^2_{N12}}^{\mathrm{T}}(\gamma). \end{aligned} \tag{15}$$

- We took the next convention:

$$[\mathcal{M}^2_{diag}]_I = R_I^T \mathcal{M}_I^2 R_I \quad I = S, A, C. \tag{16}$$

- We obtained analytical expressions to the masses of the charged states

$$m^2_{H_1^\pm} = -\frac{v^2}{2}(f-h) \tag{17}$$

$$m^2_{H_2^\pm} = \frac{1}{2}(\gamma_3^2 h - 8gv_2^2 + 9hv_3^2 - f(\gamma_3^2 + v_3^2)). \tag{18}$$

- After the EWSB it remains a residual symmetry $\mathcal{Z}_2$, that is going to have different changes associated with the particles from the model. We summarize in the next table:

Das and Dey (2014)

Neutral scalar		Pseudoscalars		Charged scalars	
h_0	Odd	A_1	Odd	$H_1^\pm$	Odd
H_1	Even	A_2	Even	$H_2^\pm$	Even
H_2	Even				

Table 1: The $\mathcal{Z}_2$ assignment for the physical states H_1, H_2, h_0, $A_{1,2}$ and $H^\pm_{1,2}$.

Higgs self-couplings

- The Higgs trilinear self-couplings are defining as:

$$\lambda_{ijk} = \frac{-i\partial^3 V}{\partial H_i \partial H_j \partial H_k}. \tag{19}$$

- Some of the trilinear self-couplings are:

$$g_{h_0 h_0 h_0} = 0,$$

$$g_{A_1 A_1 A_1} = 0,$$

Per Osland et al (2008); John F. Gunion and Howard E. Haber (2003); Barradas-Guevara et al. (2014)

Proceeding

- We made a scan in the parameter space, we imposed the stability and unitarity conditions.

  Das and Dey (2014), Barradas et al (2014), Gomez-Bock et al (2021)

Mass of neutral Higgs without CPB

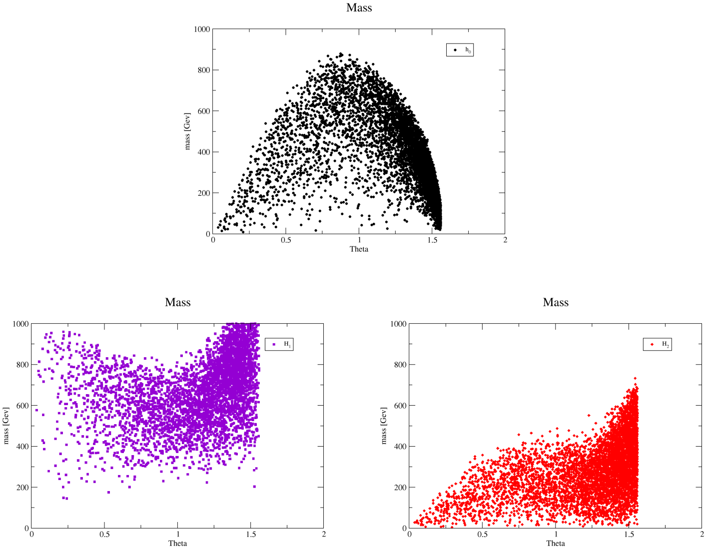


Figure 1: Dependence of the neutral scalar masses, h_0, H_1, H_2, on $\theta \in (0, \pi/2)$. The first graph shows the values of h_0, the second graph shows the values of H_1 and the last one shows the values of H_2.

Trilinear self-couplings for neutral Higgs without CPB

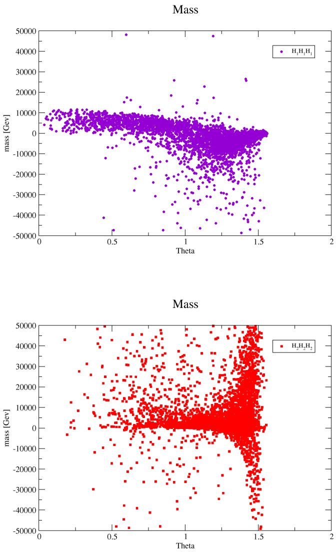


Figure 2: Dependence of the trilinear self-coupling of neutral Higgs, H_1, H_2, on $\theta \in (0, \pi/2)$. The first graph shows the values of $H_1H_1H_1$ and the second graph shows the values of $H_2H_2H_2$.

Mass of seudo-scalar without CPB

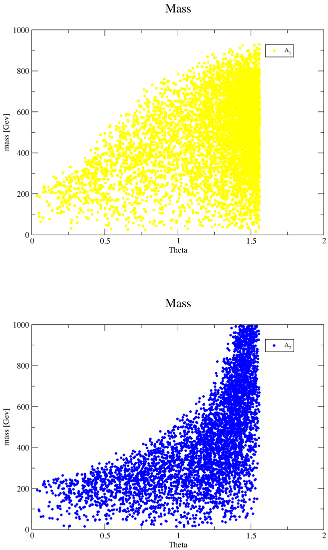


Figure 3: Dependence of the seudo-scalar masses, A_1, A_2, on $\theta \in (0, \pi/2)$. The first graph shows the values of A_1 and the second graph shows the values of A_2

Trilinear self-couplings for neutral-seudo Higgs without CPB

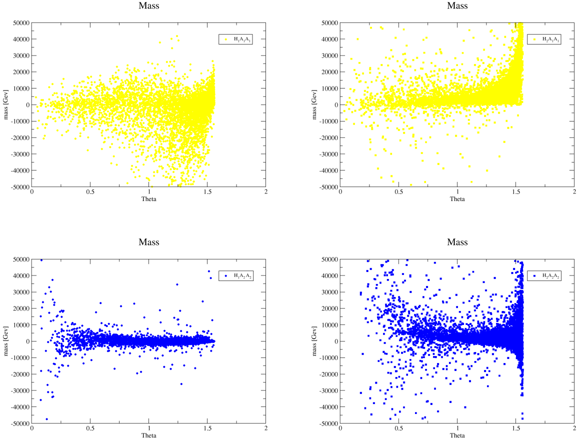
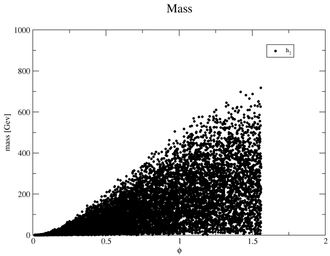


Figure 4: Dependence of the trilinear self-coupling of seudo-neutral Higgs, on $\theta \in (0, \pi/2)$. The two top graphics shows the values of $H_1A_1A_1$, $H_2A_1A_1$ and the second bottom graphics shows the values of $H_1A_2A_2$, $H_2A_2A_2$.

Mass of neutral Higgs with CPB



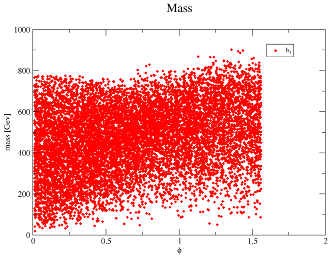


Figure 5: Dependence of the neutral scalar masses, h_2, h_3, h_4, on $\phi \in (0, \pi/2)$. The first graph shows the values of h_2 and the second graph shows the values of h_3.

Mass of neutral Higgs with CPB

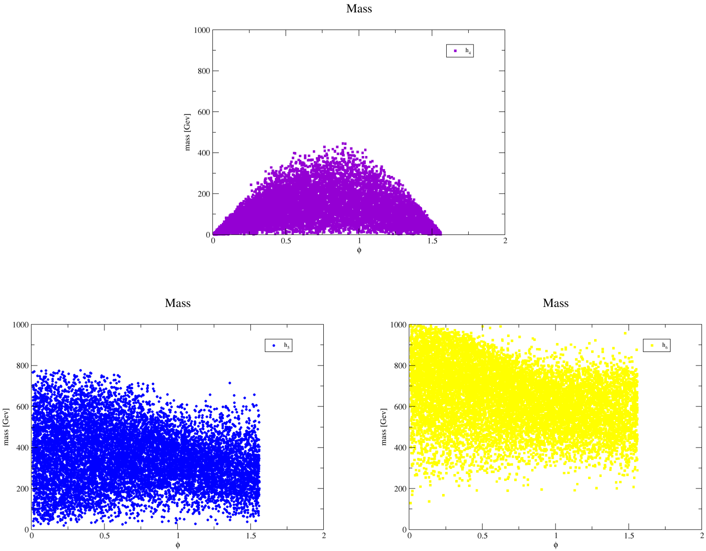


Figure 6: Dependence of the neutral scalar masses, h_2, h_3, h_4, on $\phi \in (0, \pi/2)$. The first graph shows the values of h_4, the second graph shows the values of h_5 and the last one shows the values of h_6.

Trilinear self-couplings for neutral-seudo Higgs with CPB

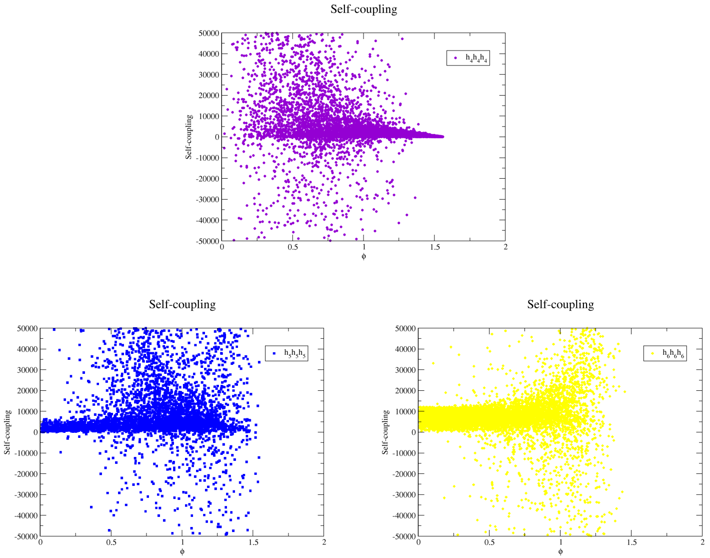


Figure 7: Dependence of the trilinear self-coupling of seudo-neutral Higgs, on $\phi \in (0, \pi/2)$. The first graph shows the values of $h_4h_4h_4$, the second graph shows the values of $h_5h_5h_5$ and the last one shows the values of $h_6h_6h_6$.

Summary

- We obtain some analytical expression for the masses of the charged Higgs imposing spontaneous CP breaking.
- We made a numerical analysis to obtain the masses of the Higgs bosons and the trilinear self-coupling.
- We found values for the parameters of the model and the angles θ, *phi*, that pass all Higgs bounds.
- There is a residual symmetry $\mathcal{Z}_2$ as in the normal vev. Which leaves one of the neutral scalars h_2, h_3 equal to zero the trilinear self-coupling.

Thank you so much !