CP violation in the extended Standard Model with a complex singlet

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Motivation

- The CP violating of SM is insufficient to explain the baryon asymmetry in the universe
- Additional sources of CP-violation is needed. We will consider an extension of the SM with a complex singlet scalar field.
- Extension of the SM with a complex singlet and complex VEV $\rightarrow$ additional CP violating phase (cSMCS)
- IDM
- cSMCS is a part of the cIDMS (Inert Doublet Model plus Complex Singlet) Bonilla, Sokolowska, Diaz-Cruz, Krawczyk and ND, arXiv:1412.8730.
    - We consider a scenario according to which the SM-like Higgs particle, comes mostly from the SM-like doublet, with a small modification coming from the singlet.
    - The inert doublet is responsible for a dark matter in agreement with data
    - There is a possibility for strong enough first order transition at the same time spontaneous CP violation and it is important for baryogenesis.

The Model

- The model contain SM-like doublet Φ and a complex singlet χ with complex VEV
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{gf}^{SM} + \mathcal{L}_Y(\psi_f, \Phi) + \mathcal{L}_{scalar}, \quad \mathcal{L}_{scalar} = T - V$$

  - $L_{gf}^{SM} \rightarrow$ gauge boson-fermion interaction as in the SM.
  - $L_Y(\psi_f, \Phi) \rightarrow$ only Φ couple to SM fermions.
- The scalar fields

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \phi_1 + i\phi_4) \end{pmatrix}, \qquad \chi = \frac{1}{\sqrt{2}}(we^{i\xi} + \phi_2 + i\phi_3).$$

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}v \quad \text{and} \quad \langle\chi\rangle = \frac{1}{\sqrt{2}}we^{i\xi}$$

- Kinetic term of scalar sector

$$T = (D_\mu\Phi)^\dagger (D^\mu\Phi) + \partial_\mu\chi^*\partial^\mu\chi,$$

D_μ is the covariant derivative for $SU(2) \times U(1)_Y$ gauge group

$$D_\mu = \partial_\mu - igW_\mu^a t^a - ig'Y_\phi B_\mu$$

Potential

$$V = V_\Phi + V_\chi + V_{\Phi\chi}$$

- SM term

$$V_\Phi = -\tfrac{1}{2} m_{11}^2 \Phi^\dagger \Phi + \tfrac{1}{2}\lambda \left(\Phi^\dagger \Phi\right)^2 .$$

- Singlet term

$$V_S = -\frac{m_s^2}{2}\chi^*\chi - \frac{m_4^2}{2}(\chi^{*2} + \chi^2)$$
$$+\lambda_{s1}(\chi^*\chi)^2 + \lambda_{s2}(\chi^*\chi)(\chi^{*2} + \chi^2) + \lambda_{s3}(\chi^4 + \chi^{*4})$$
$$+\kappa_1(\chi + \chi^*) + \kappa_2(\chi^3 + \chi^{*3}) + \kappa_3(\chi(\chi^*\chi) + \chi^*(\chi^*\chi)).$$

- Singlet and Doublet interaction

$$V_{\Phi\chi} = \Lambda_1(\Phi^\dagger\Phi)(\chi^*\chi) + \Lambda_2(\Phi^\dagger\Phi)(\chi^{*2} + \chi^2)$$
$$+\kappa_4(\Phi^\dagger\Phi)(\chi + \chi^*).$$

Constrained Model

To simplify the model we use U(1) symmetry

$$U(1): \quad \Phi \to \Phi,\, \chi \to e^{i\alpha}\chi.$$

$< \chi >$ spontaneous breaking symmetry $\to$ To avoid having massless Nambu-Goldstone scalar keep $U(1)$-soft-breaking terms

1. $U(1)$-symmetric terms: $m_{11}^2, m_s^2, \lambda, \lambda_{s1}, \Lambda_1,$
2. $U(1)$-soft-breaking terms: $m_4^2, \kappa_{2,3},$
3. $U(1)$-hard-breaking terms: $\lambda_{s2}, \lambda_{s3}, \Lambda_2.$

$$V = -\frac{1}{2}m_{11}^2\Phi^\dagger\Phi + \frac{1}{2}\lambda\left(\Phi^\dagger\Phi\right)^2 - \frac{m_s^2}{2}\chi^*\chi + \lambda_{s1}(\chi^*\chi)^2 + \Lambda_1(\Phi^\dagger\Phi)(\chi^*\chi)$$
$$-\frac{m_4^2}{2}(\chi^{*2} + \chi^2) + \kappa_2(\chi^3 + \chi^{*3}) + \kappa_3[\chi(\chi^*\chi) + \chi^*(\chi^*\chi)].$$

Constrained Potential

$$V = -\frac{1}{2}m_{11}^2\Phi^\dagger\Phi + \frac{1}{2}\lambda\left(\Phi^\dagger\Phi\right)^2 - \frac{m_s^2}{2}\chi^*\chi + \lambda_{s1}(\chi^*\chi)^2 + \Lambda_1(\Phi^\dagger\Phi)(\chi^*\chi)$$
$$-\frac{m_4^2}{2}(\chi^{*2}+\chi^2) + \kappa_2(\chi^3+\chi^{*3}) + \kappa_3[\chi(\chi^*\chi)+\chi^*(\chi^*\chi)].$$

- Parameters $\rightarrow$ $m_{11}^2,\ m_s^2,\ m_4^2,\ \lambda_{s1},\ \lambda,\ \Lambda_1,\ \kappa_2,\ \kappa_3.$

  If real $\rightarrow$ No explicit CP violation

- Vacua with spontaneous CP violation

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}v \quad \text{and} \quad \langle\chi\rangle = \frac{1}{\sqrt{2}}we^{i\xi}$$

- Spontaneous CP violation $\rightarrow$ relevant parameters $m_4^2,\ \kappa_2,\ \kappa_3$
- Positivity conditions

$$\lambda > 0,$$
$$\lambda_{s1} > 0,$$
$$\bar{\lambda}_{1S} = \Lambda_1 + \sqrt{2\lambda\lambda_{s1}} > 0.$$

Mass matrix

The mass matrix that describes the singlet-doublet mixing, in the basis of neutral fields ϕ_1, ϕ_2, ϕ_3:

$$M = \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{pmatrix}$$

- $\xi \neq 0$ (complex VEV for Singlet)

  $$M_{11} = v^2 \lambda$$

  $$M_{12} = vw\Lambda_1 \cos\xi$$

  $$M_{13} = vw\Lambda_1 \sin\xi$$

  $$M_{22} = \frac{w}{2\cos\xi}(3\sqrt{2}\kappa_2 + \sqrt{2}\kappa_3(1 + 2\cos 2\xi) + 4\lambda_{s_1}\cos^2\xi)$$

  $$M_{23} = w(-3\sqrt{2}\kappa_2 + \sqrt{2}\kappa_3 + 2\lambda_{s_1}\cos\xi)\sin\xi$$

  $$M_{33} = 2w\lambda_{s_1}\sin^2\xi$$

- $\xi = 0$ (real VEV for Singlet)

  $$M_{11} = v^2 \lambda_1$$

  $$M_{12} = vw\Lambda_1$$

  $$M_{22} = w(\frac{3}{\sqrt{2}}(\kappa_2 + \kappa_3) + 2w\lambda_{s_1})$$

  $$M_{33} = m_4^2 - \frac{m_s^2}{2} + \frac{1}{2}v^2\Lambda_1 + w(w\lambda_{s_1} + \sqrt{2}(-3\kappa_2 + \kappa_3)).$$

Mass eigenstate

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}.$$

$R \quad \rightarrow \quad$ The rotation matrix $R = R_1 R_2 R_3$ ($c_i = \cos\alpha_i, s_i = \sin\alpha_i$):

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

$$R = R_1 R_2 R_3 = \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix}.$$

Physical mass

Diagonalization of M^2_{mix} gives the physical mass

$$RM^2_{mix}R^T = diag(M^2_{h_1}, M^2_{h_2}, M^2_{h_3})$$

Physical higgs masses

$$M^2_{h_1} \simeq v^2\lambda \qquad \rightarrow \text{The SM-like Higgs boson mass, 125 GeV}$$

$$M^2_{h_{2,3}} = \frac{1}{2}(M_{22} + M_{33} \mp \sqrt{(M_{22} + M_{33})^2 + 4M^2_{23}})$$

The composition of h_1 in ϕ_1,ϕ_2,ϕ_3

$$h_1 = c_1c_2\phi_1 + (c_3s_1 - c_1s_2s_3)\phi_2 + (c_1c_3s_2 + s_1s_3)$$

$$\phi_1 = c_1c_2h_1 - c_2s_1h_2 - s_2h_3.$$

Extremum conditions

- The complex singlet VEV can be rewritten as

$$\langle\chi\rangle = \frac{1}{\sqrt{2}} w e^{i\xi} = \underbrace{\frac{1}{\sqrt{2}} w \cos\xi}_{w_1} + i \underbrace{\frac{1}{\sqrt{2}} w \sin\xi}_{w_2}; \qquad w^2 = w_1^2 + w_2^2$$

$$\left.\frac{\partial V}{\partial \Phi}\right|_{\substack{<\phi_1> \\ <\chi> \\ <\chi^*>}} = 0,$$

$$\left.\frac{\partial V}{\partial \chi}\right|_{\substack{<\phi_1> \\ <\chi> \\ <\chi^*>}} = 0,$$

$$\left.\frac{\partial V}{\partial \chi^*}\right|_{\substack{<\phi_1> \\ <\chi> \\ <\chi^*>}} = 0$$

Extremum conditions

Set of three equation:

1. $-2m_{11}^2 + 2\lambda v^2 + \Lambda_1 w^2 = 0$
2. $w_1(-m_s^2 - 2m_4^2 + v^2\Lambda_1 + 2w^2\lambda_{s1}) + 3\sqrt{2}(w_1^2 - w_2^2)\kappa_2 + \sqrt{2}(3w_1^2 + w_2^2)\kappa_3 = 0$
3. $w_2(-m_s^2 + 2m_4^2 + v^2\Lambda_1 + 2w^2\lambda_{s1} - 2\sqrt{2}w_1(3\kappa_2 + \kappa_3) = 0.$

From (2) and (3) and $w_1, w_2 \neq 0$

$$\Rightarrow \quad -4m_4^2 w_1 w + 3R_2(3w_1^2 - w_2^2) + R_3 w^2 = 0 \quad \rightarrow \text{CP} \quad \text{violation}$$

The parameters (R_2, R_3) with dimension $[M]^2$ are:

$$R_2 = \sqrt{2} w \kappa_2$$

$$R_3 = \sqrt{2} w \kappa_3$$

Region for possible CP violation

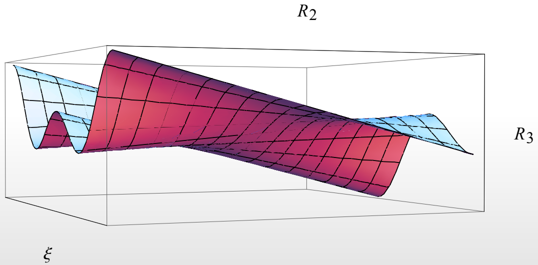
- m_4^2, R_2, R_3, ξ $(w_1^2 \geq 0\ ,\ w_2^2 > 0)$

$$-4m_4^2 w_1 w + 3R_2(3w_1^2 - w_2^2) + R_3 w^2 = 0$$

For better understanding

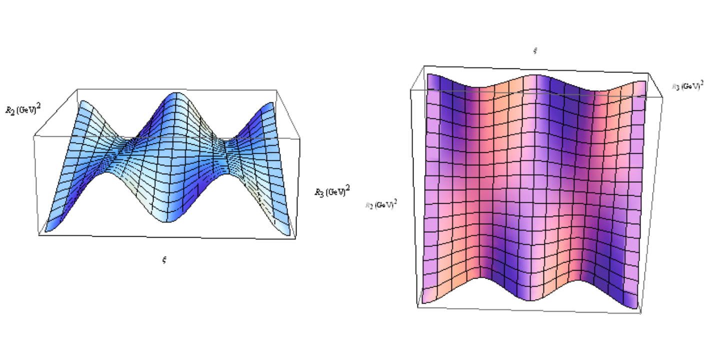
$$-4m_4^2 \cos\xi + 3R_2(1 + 2\cos 2\xi) + R_3 = 0$$

Figure: (R_2, R_3, ξ), CP violation region for fix value of m_4^2



Region for possible CP violation

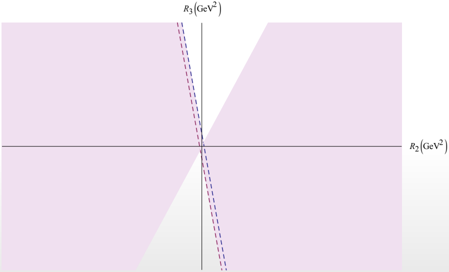
Figure: (R_2, R_3, ξ), CP violation region for fix value of m_4^2



Region for CP violation

$$-4m_4^2\cos\xi + 3R_2(1+2\cos 2\xi) + R_3 = 0$$

Figure: (R_2, R_3), CP violation is possible in the colored part

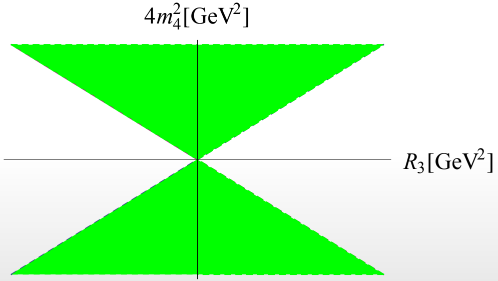


$R_2 = 0$

$$-4m_4^2 + R_3 \cos\xi = 0$$

$$-1 < \cos\xi < 1 \rightarrow -1 < \frac{R_3}{4m_4^2} < 1$$

Figure: (m_4^2, R_3) CP violation is possible in the colored region



$R_3 = 0$

$$-4m_4^2 \cos\xi + 3R_2(1 + 2\cos 2\xi) = 0$$

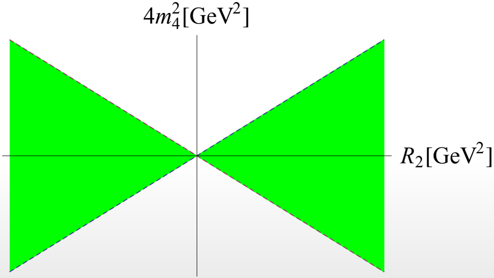


Figure: (m_4^2, R_2), CP violation is possible in the colored region

Numerical Analysis

A numerical analysis of the parameters of the SM+CS model on the allowed regions (in accordance with the extremum conditions and under the positivity and the pertubativity conditions) in the relevant ranges:

$$-1 < \Lambda_1 < 1, 0 < \lambda_{s1} < 1, \quad -1 < \rho_{2,3} < 1, \quad 0 < \xi < \pi$$

$$0.2 < \lambda_1 < 0.3$$

We performed the scanning for w, setting the variables:

$$-90000 < \mu_1^2, \mu_2^2, m_{11}^2 < 90000$$

Numerical Analysis

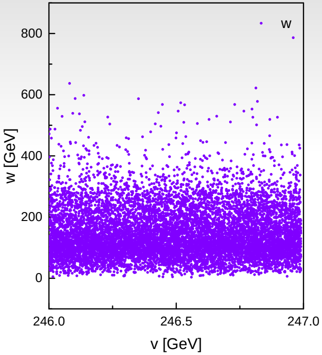


Figure: The correlation between v and w. The result shows that Λ_1 must be positive.

$$246GeV < v < 247GeV$$

Numerical Analysis

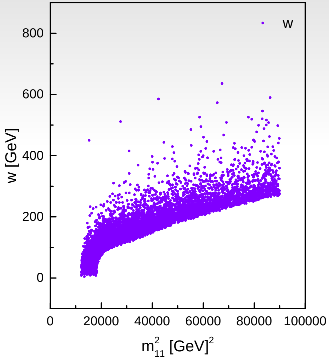


Figure: the correlation between the parameters m_{11}^2 and w for the VEV of complex singlet. The result shows that m_{11}^2 must be positive and grater than SM higgs mass square.

Numerical Analysis

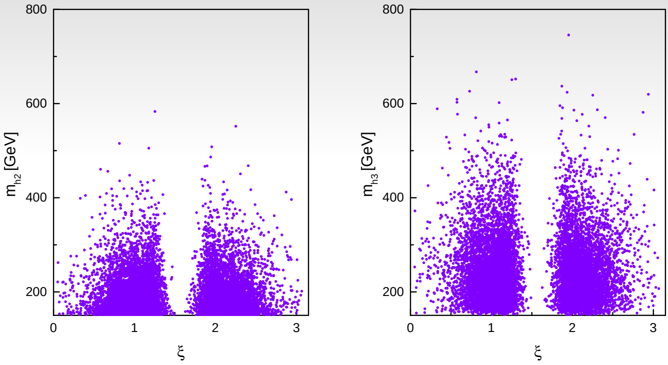
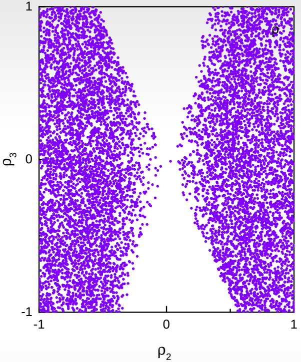


Figure: The correlation between masses m_{h_2} and m_{h_3} with ξ.

$$M_{h_3} > M_{h_2} > 150$$

Numerical Analysis



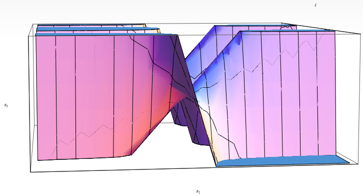


Figure: The correlation between ρ_2 and ρ_3.

Numerical Analysis

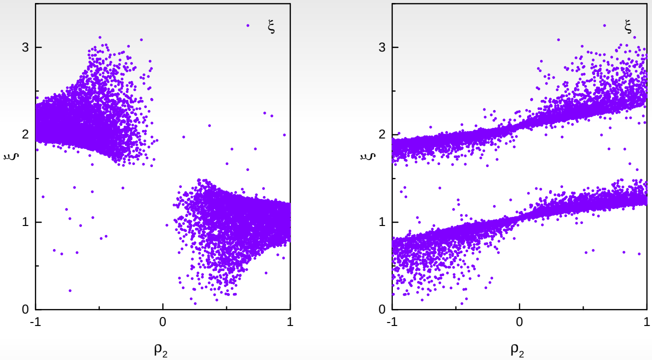


Figure: The correlation between (ρ_2, ξ) and (ρ_3, ξ).

Conclusion

- This model contains a SU(2) doublet as in the SM and a complex singlet with a complex VEV.
- This model provide source of spontaneous CP violation
- At least one cubic term is needed in order to have CP violation in the model.
- The analysis of this simple model was performed as a part of full analyzes of the cIDMS model which was confronted with LHC data for 125 GeV, precision data STU as well as astro data on dark matter .