CP-violation in complex-singlet extension of 2HDM (2HDMS)

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Work in progress in collaboration with Gudrid Moortgat-Pick

CP-violation

- Baryon-asymmetry of the universe $\rightarrow$ additional sources of CP-violation beyond SM is 'necessary'.
- It is possible to have additional CPV in models with extended scalar sectors.
- Constraints come from :
  1. EDM experiments
  2. Collider experiments
  3. Requirement from observed baryon-asymmerty.
- In this talk, I will explore the prospect of CP-violation in complex-singlet extension of 2HDM, study the impact of EDM bounds.

CP-violation in 2HDM

The most general 2HDM scalar potential :

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

- Symmetries of the potential, can make many of the complex phases go away. See Talk by *Odd Magne Ogreid on Monday*
- Exact $\mathcal{Z}_2$ symmetry i.e $m_{12}^2 = \lambda_6 = \lambda_7 = 0 \rightarrow$ no CP-violation, the phase of λ_5 can be rotated away, by a global U(2) transformation of the potential. No CP-violation.*Ilya F. Ginzburg and Maria Krawczyk (Arxiv:hep-ph/0408011)*
- Softly-broken $\mathcal{Z}_2$-symmetry i.e $m_{12}^2 \neq 0, \lambda_6, \lambda_7 = 0$ CP-violation is possible. In the alignment limit, CP-violation becomes negligible. Imagainary part of *all* possible U(2)-invariants≈0. *John F. Gunion and Howard E Haber (Arxiv:hep-ph/0506227)*

Yukawa-aligned 2HDM

- Hard breaking of $\mathcal{Z}_2$ i.e $m_{12}^2, \lambda_6, \lambda_7 \neq 0$, CP-violation can be significant.

  S. Kanemura, M.Kubota and K. Yagyu (Arxiv:2004.03943)

$$\mathcal{L}_{\text{yukawa}} = \sum_{k=1}^{2} \left(\bar{Q}_L y_{u,k}^{\dagger} \tilde{\Phi}_k u_R + \bar{Q}_L y_{d,k} \Phi_k d_R + \bar{L}_L y_{e,k} \Phi_k e_R \right)$$

- In the absence of $\mathcal{Z}_2$ symmetry, to avoid tree-level FCNC, Yukawa matrices associated with the two doublets are assumed to be proportional to each other. *A. Pich and P. Tuzon (Arxiv:0908.1554)*

$$y_{f,2} = \zeta_f \; y_{f,1}$$

- ζ can be complex and the source of CP-violation.
- In 2HDM (Yukawa-aligned), in the *exact* alignment limit, the CP-violation stems from Yukawa sector and not from the CP-mixing in the scalar sector.
- Also the Yukawa interaction of the 125 GeV Higgs is CP-conserving in the alignment limit.

2HDM + complex singlet (2HDMS)

There are two major motivation to go to the complex singlet extension of 2HDM are :

1. The scalar sector of 2HDMS resembles that of NMSSM, when the complex scalar is charged under a $\mathcal{Z}_3$ symmetry.

2. The model can accommodate a dark matter component when the complex scalar is charged under a $\mathcal{Z}_2'$ symmetry, as well as an excess such as 95 GeV observed at CMS as well as LEP in $\gamma\gamma$ and $b\bar{b}$ final state.

3. We would investigate whether, there are additional (physical) sources of CP-violation in 2HDMS.

2HDMS potential-$\mathcal{Z}_2'$ symmetric case

$$V_{\text{2HDMS}} = V_{\text{2HDM}} + V_S$$

$$\begin{aligned} V_S &= m_S^2 S^\dagger S + \left[\frac{m_S'^2}{2} S^2 + h.c.\right] + \left[\frac{\lambda_1''}{24} S^4 + h.c.\right] + \left[\frac{\lambda_2''}{6}(S^2 S^\dagger S) + h.c.\right] \\ &+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + S^\dagger S[\lambda_1' \Phi_1^\dagger \Phi_1 + \lambda_2' \Phi_2^\dagger \Phi_2] + [S^2(\lambda_4' \Phi_1^\dagger \Phi_1 + \lambda_5' \Phi_2^\dagger \Phi_2) + h.c.] \end{aligned}$$

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&+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + S^\dagger S[\lambda_1' \Phi_1^\dagger \Phi_1 + \lambda_2' \Phi_2^\dagger \Phi_2] + [S^2(\lambda_4' \Phi_1^\dagger \Phi_1 + \lambda_5' \Phi_2^\dagger \Phi_2) + h.c.] \\
&+ [\lambda_6' \Phi_1^\dagger \Phi_2 S^\dagger S + h.c] + [\lambda_7' \Phi_1^\dagger \Phi_2 S^2 + h.c] + [\lambda_8' \Phi_2^\dagger \Phi_1 S^2 + h.c]
\end{aligned}$$

- Altough $m_S'^2$, λ_1'', λ_2'', λ_4', λ_5', λ_6' and λ_7', are all in principle complex, only $\text{Im}(\lambda_6')$, $\text{Im}(\lambda_7')$ and $\text{Im}(\lambda_8')$ can introduce mixing between scalar and pseudoscalars, due to the presence of $\Phi_1^\dagger \Phi_2$ term.
- Hard $\mathcal{Z}_2$-breaking of the 2HDM potential is essential here as well for CP-violation.

$\mathcal{Z}_2'$ symmetric case - can we get dark matter and CP-violation simultaneously?

- In order to accommodate a dark matter candidate, we need $S = v_S + h_S + ia_S$ ie. at least one of the component fields acquire zero vev and two separate $\mathcal{Z}_2$ symmetry should be imposed on the two fields.

- Two separate $\mathcal{Z}_2$ on the two component fields of S can easily be imposed when the coefficients are real.

- Real coefficients are sufficient to get dark matter, not necessary.

- The necessary conditions are λ_4', λ_5', $m_S'^2$ are real, Re$[\lambda_7'] =$ Re$[\lambda_8']$, Im$[\lambda_7'] =$ -Im$[\lambda_8']$, Im$[\lambda_1''] =$ -2$\times$Im$[\lambda_2'']$.

- In that case we will be left with three independent phases, of λ_6', λ_7' and λ_1''.

- In addition, to be in the alignment limit, one needs Re$[\lambda_1'] =$ -2$\times$Re$[\lambda_4']$.

Minimization of the potential in the Higgs basis :

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1^0 + iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2^0 + ih_3^0) \end{pmatrix}$$

$$\begin{aligned}
m_{11}^2 &= \frac{1}{2}\lambda_1 v^2 + \frac{1}{2}\lambda_1' v_S^2 + \mathrm{Re}[\lambda_4'] v_S^2, \\
\mathrm{Re}[m_{12}^2] &= \frac{1}{2}(\mathrm{Re}[\lambda_6] v^2 + \mathrm{Re}[\lambda_6'] v_S^2 + \mathrm{Re}[\lambda_7'] v_S^2 + \mathrm{Re}[\lambda_8'] v_S^2) \\
\mathrm{Im}[m_{12}^2] &= \frac{1}{2}(\mathrm{Im}[\lambda_6] v^2 + \mathrm{Im}[\lambda_6'] v_S^2 + \mathrm{Im}[\lambda_7'] v_S^2 - \mathrm{Im}[\lambda_8'] v_S^2) \\
m_S^2 &= -(\mathrm{Re}[m_S'^2] + \frac{1}{2}\lambda_1' v^2 + \mathrm{Re}[\lambda_4'] v^2) + \left(\frac{\mathrm{Re}[\lambda_1'']}{12} + \frac{\mathrm{Re}[\lambda_2'']}{3} + \frac{\mathrm{Re}[\lambda_3'']}{4}\right) v_S^2 \\
\mathrm{Im}[m_S'^2] &= \left(\frac{\mathrm{Im}[\lambda_1'']}{12} + \frac{\mathrm{Im}[\lambda_2'']}{6}\right) v_S^2 + \mathrm{Im}[\lambda_4'] v^2
\end{aligned}$$

Dark Matter mass

$$m_{\mathrm{DM}}^2 = -2\mathrm{Re}[m_S'^2] - \frac{1}{3} v_S^2 (\mathrm{Re}[\lambda_1''] + \mathrm{Re}[\lambda_2'']) - 2v^2 \mathrm{Re}[\lambda_4']$$

Mass-matrix and CP-mixing in the scalar sector

In the Higgs-basis

$$\mathcal{M}^2_{ij} = \left(\begin{array}{c|ccc|c} m_{11} & 0 & 0 & 0 & 0 \\ \hline 0 & m_{22} & 0 & m_{24} & 0 \\ 0 & 0 & m_{33} & m_{34} & 0 \\ 0 & m_{24} & m_{34} & m_{44} & 0 \\ \hline 0 & 0 & 0 & 0 & m_{55} \end{array}\right)$$

$$\begin{aligned}
m_{11} &= \lambda_1 v^2 = m_h^2;\, m_h = 125\text{GeV} \\
m_{22} &= -m_{22}^2 + \left(\frac{\lambda_2' + \text{Re}[\lambda_5']}{2}\right) v_S^2 + \left(\frac{\lambda_3 + \lambda_4 + \text{Re}[\lambda_5]}{2}\right) v^2 \\
m_{24} &= v v_S \text{Re}[\lambda_6' + 2\lambda_7'] \\
m_{33} &= -m_{22}^2 + \left(\frac{\lambda_2' + \text{Re}[\lambda_5']}{2}\right) v_S^2 + \left(\frac{\lambda_3 + \lambda_4 - \text{Re}[\lambda_5]}{2}\right) v^2 \\
m_{34} &= v v_S \text{Im}[\lambda_6' + 2\lambda_7'] \;\; \rightarrow \text{Mixing in the scalar sector} \\
m_{44} &= \frac{1}{6} v_S^2 (\text{Re}[\lambda_1''] + 4\text{Re}[\lambda_2''] + 3\text{Re}[\lambda_3'']) \\
m_{55} &= -2\text{Re}[m_S'^2] - \left(\frac{\text{Re}[\lambda_1''] + \text{Re}[\lambda_2'']}{3}\right) v_S^2 - 2\text{Re}[\lambda_4'] v^2 = m_{\text{DM}}^2
\end{aligned}$$

Yukawa sector

In terms of fermion mass eigenstates,

$$\mathcal{L}_{\text{yukawa}} = -\sum_{f=u,d,e}\left\{\bar{f}_L M_f f_R + \sum_{j=1}^{3}\bar{f}_L\left(\frac{M_f}{v}\kappa_f^j\right) f_R H_j^0 + h.c.\right\}$$
$$-\frac{\sqrt{2}}{v}\left\{-\zeta_u \bar{u}_R (M_u^\dagger V_{\text{CKM}}) d_L + \zeta_d \bar{u}_L (V_{\text{CKM}} M_d) d_R + \zeta_e \bar{\nu}_L M_e e_R\right\} H^+ + h.c.$$

$$\kappa_f^j = \mathcal{R}_{1j} + [\mathcal{R}_{2j} + i(-2I_f)\mathcal{R}_{3j}]\,|\zeta_f|e^{i(-2I_f)\theta_f}$$

- In 2HDM, in the alignment limit ($R_{ij} = \delta_{ij}$), the CP-violation in the Yukawa sector can not come from the CP-mixing in the scalar sector. It must come from the phases of the Yukawa matrices.
- In 2HDMS, there can be additional source of CP-violation from the scalar sector mixing.
- In both cases the Yukawa couplings of the H_1^0 does not contain any CP-violating phases and therefore SM-like.

Electric Dipole Moments

$$H_{\text{EDM}} = -d_f \frac{\vec{S}}{|\vec{S}|} \cdot \vec{E}$$

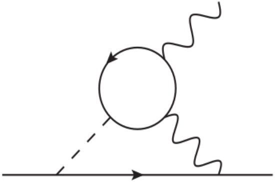
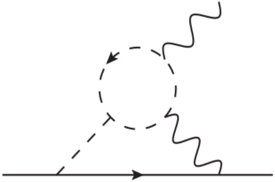
Under the time reversal transformation:
$\mathcal{T}(\vec{S}) = -\vec{S}$ and $\mathcal{T}(\vec{E}) = +\vec{E}$ the sign of this term H_{EDM} is flipped. CP symmetry is broken.
In EFT language,

$$\mathcal{L}_{\text{EDM}} = -\frac{d_f}{2} \bar{f} \sigma^{\mu\nu} (i\gamma^5) f F_{\mu\nu}$$

The most recent bounds on electron EDM

$|d_e| < 1.1 \times 10^{-29}$e.cm$(ThO)$ ACME collaboration, nature 562, 355 (2018)
$|d_e| < 4.1 \times 10^{-30}$e.cm$(HfF^+)$ T. S. Roussy et. al., Science 381, 46 (2023)

Bar-Zee diagrams

$$d_f = d_f(\text{fermion}) + d_f(\text{Higgs}) + d_f(\text{gauge})$$

Each contribution $d_f(X)$ further constists of

$$d_f(X) = d_f^{\gamma}(X) + d_f^{Z}(X) + d_f^{W}(X)$$

- The gauge boson loops contribute negligibly in the alignment limit.
- The fermion and scalar boson loops contribute at equivalent strength.
- One loop contribution is suppressed by at least 4-5 orders of magnitude.

Results

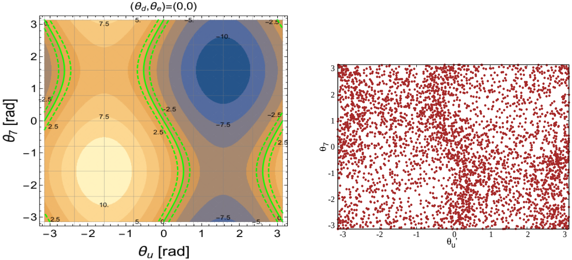


Figure: $m_{h_2} = 280\text{GeV},\ m_{h_3} = m_{h^{\pm}} = 230$ GeV.

(left):*S. Kanemura, M.Kubota and K. Yagyu (Arxiv:2004.03943)* Yukawa-aligned 2HDM scenario, (right) 2HDMS scenario.

Next we chose $[\theta_u, \theta_7] = \left[\frac{\pi}{2}, \frac{\pi}{2}\right] \rightarrow d_e = -12.7 \times 10^{-29}$ e.cm.

For the chosen bechmark, calculated EDM for 2HDMS scenario, constrained 2HDMS parameters.

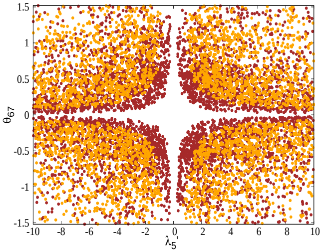


Figure: Orange : m_{h_4}=200 GeV, Maroon : m_{h_4}=95 GeV

I chose the benchmark in Yukawa-aligned 2HDM scenario with
$[\theta_u, \theta_7] = \left[\frac{\pi}{2}, \frac{\pi}{2}\right]$, $m_{h_2} = 280$GeV, $m_{h_3} = m_{h^\pm} = 230$ GeV.
$\theta_{67} = tan^{-1}\left(\frac{Im[\lambda_6' + 2\lambda_7']}{Re[\lambda_6' + 2\lambda_7']}\right)$

Summary

- Hard breaking of $\mathcal{Z}_2$-symmetry of 2HDM in the alignment limit is necessary for CP-violation. This statement holds even in complex-singlet extension ($\mathcal{Z}_2'$-symmetric) of 2HDM.
- It is possible to accommodate DM and CP-violation in 2HDMS, with restrictions on complex couplings.
- The fine-tuned cancellations required to satisfy EDM bounds in Yukawa-aligned 2HDM can be alleviated in 2HDMS.

Further things to do

- Comparison with the $\mathcal{Z}_3$ symmetric (NMSSM-like) complex singlet sector
- Imposing existing experimental contraints on the parameter space, DM constraints.
- Constucting CP-odd observables to probe CP-violating effects, *eg.* azimuthal angles, asymmetries, impact of beam polarization in lepton colliders.
- Can the amount of allowed CP-violation in this model, be sufficient for baryogenesis?

Thank You

Back-Up

Mass-matrix in the Higgs basis in 2HDM with hard $\mathcal{Z}_2$-breaking.

$$\begin{pmatrix} \lambda_1 & Re[\lambda_6] & -Im[\lambda_6] \\ Re[\lambda_6] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + Re[\lambda_5]) & -\frac{1}{2} Im[\lambda_5] \\ -Im[\lambda_6] & -\frac{1}{2} Im[\lambda_5] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - Re[\lambda_5]) \end{pmatrix}.$$

Alignment condition for h_1 implies λ_6 is 0. One can take $Im[\lambda_5] = 0$ by using the phase redefinition, $(\Phi_1^\dagger \Phi_2) \to e^{-Arg[\lambda_5]/2}(\Phi_1^\dagger \Phi_2)$
and we also redefine the other complex parameters as
$\mu_3^2 e^{-Arg[\lambda_5]/2} \to \mu_3^2, \lambda_6 e^{-Arg[\lambda_5]/2} \to \lambda_6$ and $\lambda_7 e^{-Arg[\lambda_5]/2} \to \lambda_7$