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

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Work in collaboration with Gudrid Moortgat-Pick, to appear

CP-violation

- Why look into CP-violation?
- Baryon-asymmetry of the universe → Sakharov conditions → additional sources of CP-violation beyond SM is necessary.
- It is possible to have additional CPV in models with extended scalar sectors.
- Constraints/discovery come from :
  1. EDM experiments
  2. Collider experiments
  3. Requirement from observed baryon-asymmerty.
- I will explore the possibility of CP-violation in complex-singlet extension of 2HDM.
- We would assume CPV is mostly in the BSM sector.
- Explore the EDM bounds on CP-violating phases.
- Interplay with other constraints : HiggsBounds, unitarity, DM observables etc.
- Probe at collider.

CP-violation in general 2HDM

The most general 2HDM scalar potential :

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

- For significant CPV in 2HDM in the exact alignment limit, hard breaking of $\mathcal{Z}_2$ is requred i.e $m_{12}^2, \lambda_6, \lambda_7 \neq 0$. *S. Kanemura, M.Kubota and K. Yagyu (Arxiv:2004.03943)*.
- 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)*.
- Proportionality factor ζ_f can be complex (with phase θ_f) and can be source for CP-violation.
- In Yukawa-aligned 2HDM, in the *exact* alignment limit, there is no CP-mixing between the neutral scalars. θ_f, θ_7 introduces CPV in Yukawa and trilinear couplings.
- 125 GeV is completely CP-even and SM-like in the exact alignment.

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

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.

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

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

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- 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 assume $S = v_S + h_S + ia_S$ ie. at least one of the component fields acquire zero vev.
- The necessary conditions are :
  1) λ'_4, λ'_5, m'^2_S are real,
  2) Re$[\lambda'_7]$ = Re$[\lambda'_8]$, Im$[\lambda'_7]$ = -Im$[\lambda'_8]$,
  3) Im$[\lambda''_1]$ = -2×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×Re$[\lambda'_4]$.

Mass-matrix and CP-mixing in the neutral scalar sector

In the Higgs-basis

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

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

Constraints from 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,

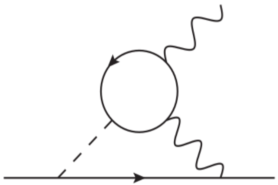
$$\mathcal{L}_{\text{EDM}} = -\frac{d_f}{2} \bar{f} \sigma^{\mu\nu} (i\gamma^5) f F_{\mu\nu}$$

The most recent bounds on electron EDM and neutron EDM

$$|d_e| < 4.1 \times 10^{-30} \text{e.cm}$$ T. S. Roussy et. al., Science 381, 46 (2023)

$$|d_n| < 1.1 \times 10^{-26} \text{e.cm}$$ C. Abel et. al., Phys.Rev.Lett. 124 (2020) 8, 081803

Bar-Zee diagrams



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

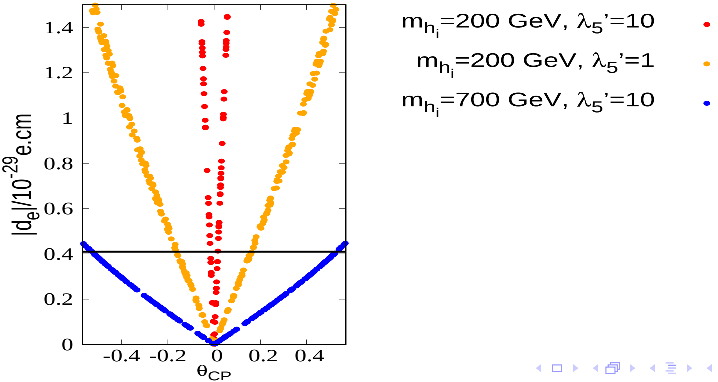
Each contribution $d_f(X)$ further constists of

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

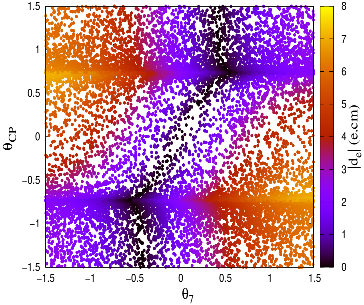
- The gauge boson loops contribute negligibly in the alignment limit.
- The fermion and charged scalar loops contribute at equivalent strength.

Results

In Z_2-symmetric 2HDMS, there are three sources of CPV.
(1) θ_{CP}, (2) θ_7, (3) θ_f
Source 1 : CPV phase in the neutral scalar mass-matrix,
$\theta_{CP} = tan^{-1}\left(\frac{Im[\lambda_6' + 2\lambda_7']}{Re[\lambda_6' + 2\lambda_7']}\right)$.



Effect of both θ_{CP} and θ_7, implying cancellation between the fermion and scalar loop contributions.



$|d_e|$ in unit of 10^{-29}.

$m_{h_i} \approx 200$ GeV and $\lambda_5' = 1$

Vary $\theta_f, \theta_7, \theta_{CP}$ all at the same time.

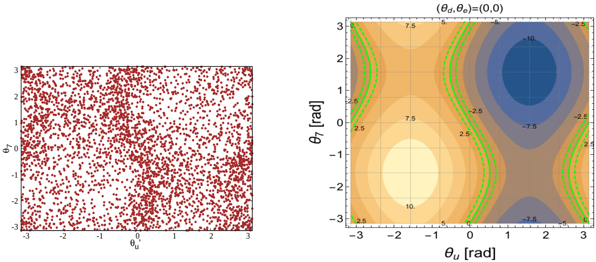


Figure: $m_{h_2} = 280\text{GeV}$, $m_{h_3} = m_{h^\pm} = 230$ GeV.

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

- The fine-tuning observed in 2HDM is alleviated in its complex-singlet extension.
- The cancellation between diagrams is more effective when the scalar masses are low.

Interplay with DM phenomenology

Trilinear and quartic couplings between DM pair and the scalars

$$
\begin{aligned}
\lambda_{a_S a_S h_1 h_1} &= -\lambda_4' \\
\lambda_{a_S a_S h_1 h_2} &= \frac{1}{2}(\mathrm{Re}[\lambda_6'] - 2\mathrm{Re}[\lambda_7']) \\
\lambda_{a_S a_S h_2 h_2} &= \frac{1}{4}(\lambda_2' - 2\lambda_5') \\
\lambda_{a_S a_S h_1 a_2} &= -\frac{1}{2}(\mathrm{Im}[\lambda_6'] - 2\mathrm{Im}[\lambda_7']) \\
\lambda_{a_S a_S a_2 a_2} &= \frac{1}{4}(\lambda_2' - 2\lambda_5') \\
\lambda_{a_S a_S h_1} &= -2v\lambda_4' \\
\lambda_{a_S a_S h_2} &= \frac{1}{2}v(\mathrm{Re}[\lambda_6'] - 2\mathrm{Re}[\lambda_7']) \\
\lambda_{a_S a_S h_S} &= -\frac{1}{4}v_S(\lambda_1'' - \lambda_3'') \\
\lambda_{a_S a_S a_2} &= -\frac{1}{2}v(\mathrm{Im}[\lambda_6'] - 2\mathrm{Im}[\lambda_7'])
\end{aligned}
$$

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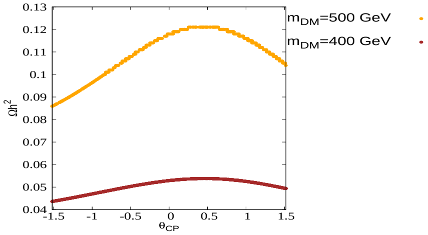
$$\lambda_{a_S a_S h_S} = -\frac{1}{4}v_S(\lambda_1'' - \lambda_3'')$$

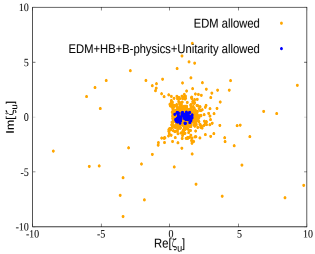
$$\lambda_{a_S a_S a_2} = -\frac{1}{2}v(\text{Im}[\lambda_6'] - 2\text{Im}[\lambda_7'])$$



$m_{h_i} \approx 200$ GeV.
$\sim 40 - 50\%$ deviation is possible in relic density calculation.

Interplay with other constraints

- Low scalar mass region looks interesting from EDM as well as future collider point of view.
- What about HB, B-physics?
- The free parameters ζ does open up allowed parameter space allowed by HiggsBounds, B-physics in the low mass region, which is also consistent with EDM bounds.

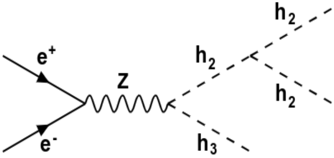


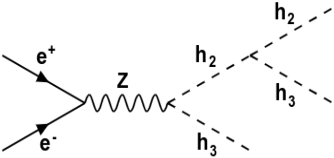
$m_{h_i} = 200$ GeV

Probing CP-violation at e^+e^- collider with trilinear couplings

- The CP-violation at the collider can be probed with CP-violating trilinear couplings.
- Simultaneous observation of the following processes will be a tell-tale sign of CP-violation.
  1. $e^+e^- \to h_2 h_2 h_3$ and $e^+e^- \to h_2 h_3 h_3$
  2. $e^+e^- \to h_4 h_4 h_3$ and $e^+e^- \to h_4 h_3 h_3$

In absence of CP-violation h_3 is the CP-odd scalar, h_2-non-standard doublet-like CP-even scalar and h_4 singlet-like scalar.
Process (1) sensitive to θ_7, Process (2) sensitive to θ_{CP}.


e+
e-
Z
h2
h3
h2
h2


e+
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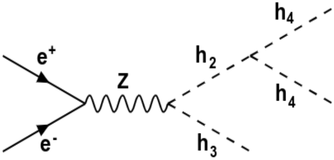
h3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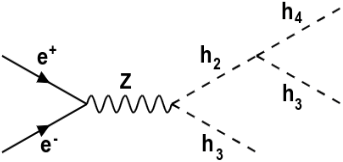
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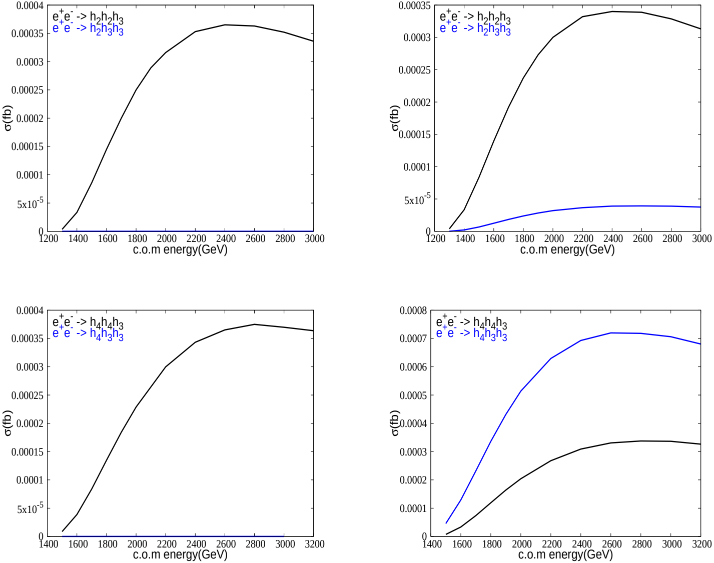


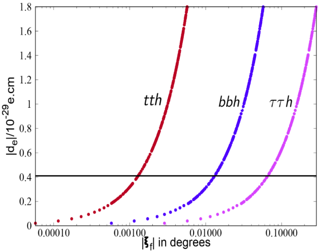
$m_{h_i} = 400$ GeV

Deviating from exact Alignment

$$\mathcal{L}_{\text{yukawa}} = -\sum_{f=u,d,e}\left\{\bar{f}_L M_f f_R + \sum_{j=1}^{3}\bar{f}_L\left(\frac{M_f}{v}\kappa_f^j\right) f_R H_j^0 + h.c.\right\}$$

$$\kappa_f^1 = \mathcal{R}_{11} + [\mathcal{R}_{21} + i(-2I_f)\mathcal{R}_{31}]\,|\zeta_f|e^{i(-2I_f)\theta_f}$$

$$\mathcal{L}_{hff} = \frac{M_f}{v}|\kappa_f|\bar{f}_L(\cos\xi_f + i\gamma_5\sin\xi_f)f_R h$$



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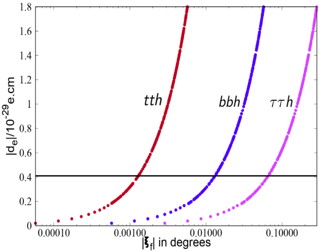

- Assuming CPV only in the 125 GeV Higgs, EDM bounds are stringent by orders of magnitude compared to future collider sensitivity.
- With other nonzero phases, relative cancellation between diagrams can lead to less restrictive bounds on ξ_f from EDM.

Summary

- While a CP-even 125 GeV Higgs is favored by the experiments, the CPV can be lurking in the extended scalar sector.
- It is possible to accommodate DM and CP-violation in 2HDMS, with restrictions on complex couplings.
- While EDM bounds put stringent constraint on individual CP-violating phases, cancellation between multiple contributions to EDM can relax such bounds.
- CP phases can impact DM relic density.
- It is possible to probe CP-violation through the trilinear coupling at the future colliders.
- Depending on the parameter space, EDM or collider bounds would be more constraining.

Ongoing and Future directions

- Probing such scenarios at future colliders, can we resolve the CP phases?
- Can the amount of allowed CP-violation in this model, be sufficient for baryogenesis?

Thank You

Back-Up

- Conditions for DM in CPV-2HDMS with Z_2 symmetry:
  The coupling asssociated with term

  $h_2 a_S \to -vvS(Im[\lambda_7'] + Im[\lambda_8'])$,

  It can be zero, when λ_7' and λ_8' are both real. However, also with $Im[\lambda_7'] = -Im[\lambda_8']$
- Yukawa matrices in the interaction basis :

$$y_f^1\prime(v_1 + \zeta_f' v_2) = m_f$$

- Yukawa matrices in the Higgs basis :

$$y_f^1 = \frac{m_f}{v}$$

Basis transformation

The fields Φ'_1 and Φ'_2 are defined in the interaction basis and Φ_1 and Φ_2 are defined in the Higgs-basis. When the vevs of the interaction basis are as follows:

$(\langle \Phi'^0_1 \rangle, \langle \Phi'^0_2 \rangle) = (v_1 e^{i\xi_1}/\sqrt{2}, v_2 e^{i\xi_2}/\sqrt{2})$,

One can make the following unitary transformation to go to the Higgs-basis.

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} e^{-i\xi_1} & 0 \\ 0 & e^{-i\xi_2} \end{pmatrix} \begin{pmatrix} \Phi'_1 \\ \Phi'_2 \end{pmatrix}, \tag{1}$$

Comparison with the ‘usual’ 2HDM-types

Model Yukawa-aligned 2HDM	ζ_u Arbitrary complex	ζ_d Arbitrary complex	ζ_l Arbitrary Complex
Type-I	$1/\tan\beta$	$1/\tan\beta$	$1/\tan\beta$
Type-II	$1/\tan\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$1/\tan\beta$	$1/\tan\beta$	$-\tan\beta$
Type-Y	$1/\tan\beta$	$-\tan\beta$	$1/\tan\beta$

Source of CPV in the general (Yukawa-aligned) 2HDM set-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 $\lambda_6 \approx 0, \quad m_h^2 = \lambda_1 v^2$.
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 $\lambda_7 e^{-Arg[\lambda_5]/2} \to \lambda_7$

Source of CPV in the general (Yukawa-aligned) 2HDM set-up

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

$$\begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + Re[\lambda_5]) & 0 \\ 0 & 0 & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - Re[\lambda_5]) \end{pmatrix}.$$

- Source of CPV in general/Yukawa-aligned 2HDM comes from

  (1) $\mathrm{Im}(\lambda_7)$ which introduces AH^+H^--type vertex.

  (2) phases of ζ-factors in the Yukawa sector.

Minimization of the potential in the Higgs basis :

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

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

Dark Matter mass

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

Yukawa

But tree-level FCNC is introduced in the Yukawa Lagrangian:

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

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

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, since here $R_{ij} \neq \delta_{ij}$.
- In both cases the Yukawa couplings of the H_1^0 does not contain any CP-violating phases and therefore SM-like in the exact Alignment limit.

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

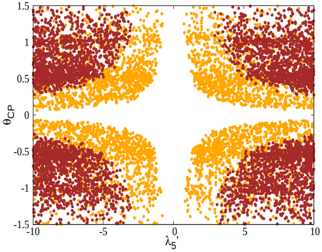

Figure: Orange : $m_{h_i} \approx 200$ GeV, Maroon : $m_{h_i} \approx 600$ GeV

I chose the benchmark in Yukawa-aligned 2HDM scenario with $[\theta_u, \theta_7] = \left[\frac{\pi}{2}, \frac{\pi}{2}\right], m_{h_2} = 280\text{GeV}, m_{h_3} = m_{h^\pm} = 230$ GeV.