Probing CP-violation in complex-2HDMS with 95 GeV at future lepton colliders

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CP-violation

- Baryon-asymmetry of the universe → 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 collider constraints as well as future projection of CP-violation in the complex-2HDMS with EDM bounds imposed.

Probing CP-nature of 125 GeV and 95 GeV excess

- The 125 GeV Higgs boson, can be a CP-mixed state.
- The CP-odd 125 GeV Higgs is ruled out at $\gtrsim 5\sigma$.
- LHC and future experiments (HL-LHC and lepton colliders) provide bounds and future projection on the CP-odd component of the Higgs.
- We investigate the CP-nature of the recently observed 95 GeV excess and what do the data tell us about its CP-nature?
- Constraints from EDM.
- Future probes at the lepton colliders.

The most general complex 2HDMS scenario

The scalar potential:

$$\begin{aligned}
V =& m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_1) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\\
&[-m_{12}^2(\Phi_1^\dagger\Phi_2) + \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}]\\
&+ m_S^2(S^\dagger S) + \lambda_1'(S^\dagger S)(\Phi_1^\dagger\Phi_1) + \lambda_2'(S^\dagger S)(\Phi_2^\dagger\Phi_2) + \frac{\lambda_3''}{4}(S^\dagger S)^2\\
&[+m_S'^2 S^2 + \mu_{S1}S^3 + \mu_{S2}S(S^\dagger S) + \mu_{11}S(\Phi_1^\dagger\Phi_1) + \mu_{22}S(\Phi_2^\dagger\Phi_2) + \mu_{12}S(\Phi_1^\dagger\Phi_2) + \mu_{21}S(\Phi_2^\dagger\Phi_1)\\
&+\frac{\lambda_1''}{4!}S^4 + \frac{\lambda_2''}{3!}(S^\dagger S)S^2 + \lambda_3'(S^\dagger S)(\Phi_1^\dagger\Phi_2) + \lambda_4' S^2(\Phi_1^\dagger\Phi_1) + \lambda_5' S^2(\Phi_2^\dagger\Phi_2)\\
&+\lambda_6' S^2(\Phi_1^\dagger\Phi_2) + \lambda_7' S^2(\Phi_2^\dagger\Phi_1) + \mathrm{h.c.}]
\end{aligned} \tag{1}$$

$$\Phi_1 = e^{i\xi_1}\begin{pmatrix}\chi_1^+\\ \frac{1}{\sqrt{2}}(v_1+\rho_1+i\eta_1)\end{pmatrix},\quad \Phi_2 = \begin{pmatrix}\chi_2^+\\ \frac{1}{\sqrt{2}}(v_2+\rho_2+i\eta_2)\end{pmatrix},\quad S = e^{i\xi_S}(v_S+\rho_S+i\eta_S) \tag{2}$$

- In the absence of complex parameters, CP-even states ρ_1, ρ_2, ρ_S will mix and give rise to CP-even mass eigenstates H_1, H_2, H_3.
- CP-odd states η_1, η_2, η_S will mix and give rise to a Goldstone state G_0 and two pseudoscalar states A_1, A_2.
- In case of CPV, 5 CP-mixed mass eigenstates will be present h_1, h_2, h_3, h_4, h_5.

We have five Higgs in mass eigenstates and 10 mixing angles

$$\mathrm{diag}(m_{h_1}^2, m_{h_1}^2, m_{h_3}^2, m_{h_4}^2, m_{h_5}^2) = RM_H^2R^T, \tag{3}$$

where the mixing matrix is as follows:

$$R = R(\alpha_{12}, \alpha_{13}, \alpha_{23}, \alpha_{14}, \alpha_{24}, \alpha_{34}, \alpha_{15}, \alpha_{25}, \alpha_{35}, \alpha_{45}) \tag{4}$$

Mixing in a simplified version of complex 2HDMS

$$\begin{aligned} V =& m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_1) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & [-m_{12}^2(\Phi_1^\dagger\Phi_2) + \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}] \\ & + m_S^2(S^\dagger S) + \lambda_1'(S^\dagger S)(\Phi_1^\dagger\Phi_1) + \lambda_2'(S^\dagger S)(\Phi_2^\dagger\Phi_2) + \frac{\lambda_3''}{4}(S^\dagger S)^2 \\ & + \mu_{S1}S^3 + \mu_{12}S(\Phi_1^\dagger\Phi_2) + \lambda_4' S^2(\Phi_1^\dagger\Phi_1) + \lambda_5' S^2(\Phi_2^\dagger\Phi_2)\mathrm{h.c.}] \end{aligned} \tag{5}$$

The CP-mixing entries in the squared-mass-matrix M_H^2.

$$\begin{aligned} M_{H14}^2 &= -\frac{1}{2}v^2\mathrm{Im}(2\lambda_6 c_\beta + \lambda_5 s_\beta) \\ M_{H24}^2 &= -\frac{1}{2}v^2\mathrm{Im}(2\lambda_7 s_\beta + \lambda_5 c_\beta) \\ M_{H34}^2 &= \mathrm{Im}\mu_{12}v \\ M_{H15}^2 &= -v\mathrm{Im}(4\lambda_4' v_S c_\beta + \mu_{12}s_\beta) \\ M_{H25}^2 &= -v\mathrm{Im}(4\lambda_5' v_S s_\beta + \mu_{12}c_\beta) \\ M_{H35}^2 &= \mathrm{Im}\left(\frac{v^2}{v_S}\mu_{12}s_\beta c_\beta - \mu_{S1}v_S\right) \end{aligned} \tag{6}$$

Yukawa couplings

we choose the specific type (type II) and therefore the reduced Yukawa couplings are as follows.

$$c_{h_i tt} = R_{i2}/\sin\beta - i\gamma_5 R_{i4}/\tan\beta \tag{7}$$

$$c_{h_i bb} = c_{h_i \tau\tau} = R_{i1}/\cos\beta - i\gamma_5 R_{i4}\tan\beta \tag{8}$$

Therefore, if we impose a limit $(\alpha_{15},\ \alpha_{25},\ \alpha_{35},\ \alpha_{45}) \to 0$

	$c_{h_i tt}$	$c_{h_i bb}/c_{h_i \tau\tau}$
h_1	$\frac{s_{12}}{s_\beta} c_{13} c_{14} - i\gamma_5 \frac{s_{14}}{t_\beta}$	$\frac{c_{12}}{c_\beta} c_{13} c_{14} - i\gamma_5 s_{14} t_\beta$
h_2	$(c_{12} c_{23} c_{24} + s_{12}(-c_{24} s_{13} s_{23} - c_{13} s_{14} s_{24}))/s_\beta$ $-i\gamma_5 (c_{14} s_{24})/t_\beta$	$(-c_{23} c_{24} s_{12} + c_{12}(-c_{24} s_{13} s_{23} - c_{13} s_{14} s_{24}))/c_\beta$ $-i\gamma_5 c_{14} s_{24} t_\beta$
h_3	$(c_{12}(-c_{34} s_{23} - c_{23} s_{24} s_{34})$ $+s_{12}(-s_{13}(c_{23} c_{34} - s_{23} s_{24} s_{34}) - c_{13} s_{14} c_{24} s_{34}))/s_\beta$ $-i\gamma_5 (c_{14} c_{24} s_{34})/t_\beta$	$(s_{12}(c_{34} s_{23} + c_{23} s_{24} s_{34})$ $+c_{12}(-s_{13}(c_{23} c_{34} - s_{23} s_{24} s_{34}) - c_{13} s_{14} c_{24} s_{34}))/c_\beta$ $-i\gamma_5 c_{14} c_{24} s_{34} t_\beta$

$\mathcal{L}_{Yukawa} = c_{h_i ff} = \frac{m_f}{v}\kappa_f(\cos\phi_f + i\gamma\sin\phi_f) = \frac{m_f}{v}(a_f + i\gamma b_f)$
ϕ_f is the measure of CPV.

Benchmark scenario

m_{h_1}	m_{h_2}	m_{h_3}	m_{h_4}	m_{h_5}	$m_{H^\pm}$	$\tilde{\mu}$	v_S
800	125	95	805	150	795	800	1000
t_β	$c_{\beta-\alpha_{12}}$	α_{13}	α_{23}	α_{14}	α_{24}	α_{34}	ξ_1, ξ_S
5	0.015	0.0	0.35	0.0	0.00662652	0.0356523	0

Table: Benchmark satisfying all theoretical and experimental constraints

Constraints from EDM

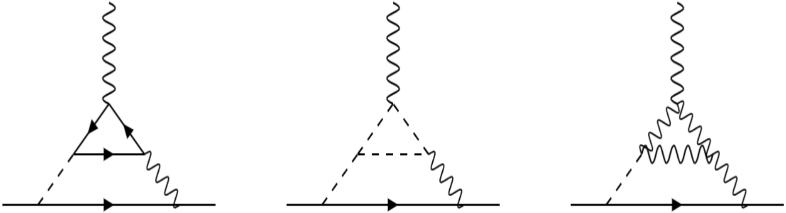
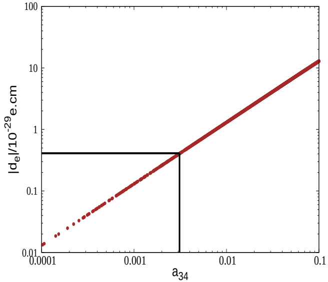
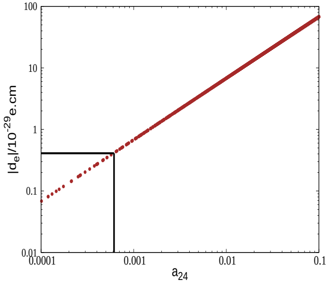


Figure: The two-loop Bar-Zee diagrams with fermion (left), scalar (middle) and gauge-boson (right) loop contributions.

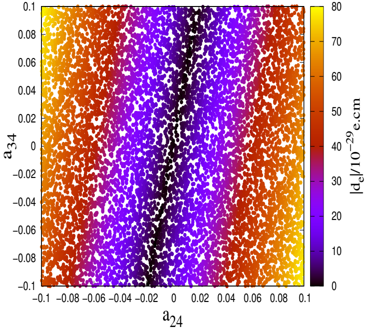
Bounds from EDM on individual phases

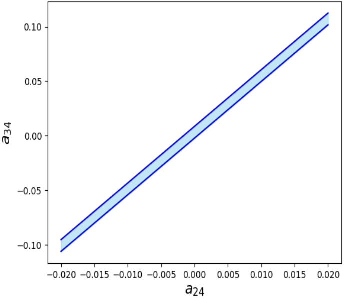




EDM bounds on individual angles $a_{34} < 0.003$ and $a_{24} < 0.0006$.

Bounds from EDM on both phases





Probing CPV with decays of H_{125} and H_{95} in $\tau\tau$ channel at e^+e^- colliders

- The process: $e^+e^- \to H_{95/125}Z, H_{95/125} \to \tau\tau$
- Probe the coupling structure of $H\tau\tau$.
- The decay modes of τ-lepton.

Notation	Decay Mode	Branching fraction
ℓ	$l^\pm\nu\bar{\nu}$	35%
1p0n	$\pi^\pm\nu$	11%
1p1n	$\rho^\pm\nu \to \pi^\pm\pi^0\nu$	26%
1p2n	$a_1^\pm\nu \to \rho^\pm\pi^0\nu \to \pi^\pm\pi^0\pi^0\nu$	10%
3p0n	$a_1^\pm\nu \to \rho^0\pi^\pm\nu \to \pi^\pm\pi^\mp\pi^\pm\nu$	9%

Relevant di-τ channels for our study.

Decay channel	Decay Mode combinations	Branching fraction
$\tau_{lep}\tau_{had}$	ℓ-1p0n	8.1%
	ℓ-1p1n	18.3%
	ℓ-1p2n	7.6%
	ℓ-3p0n	6.9%
$\tau_{had}\tau_{had}$	1p0n-1p0n	1.3%
	1p0n-1p1n	6.0%
	1p1n-1p1n	6.7%
	1p0n-1p2n	2.5%
	1p1n-1p2n	5.6%
	1p1n-3p0n	5.1%

- We focus on signal process $e^+e^- \to h_{95/125}(\tau_{had}\tau_{had})Z(l^+l^-)$.
- Major backgruound comes from SM process $e^+e^- \to Z(\tau_{had}\tau_{had})Z(l^+l^-)$.

CP-sensitive observables

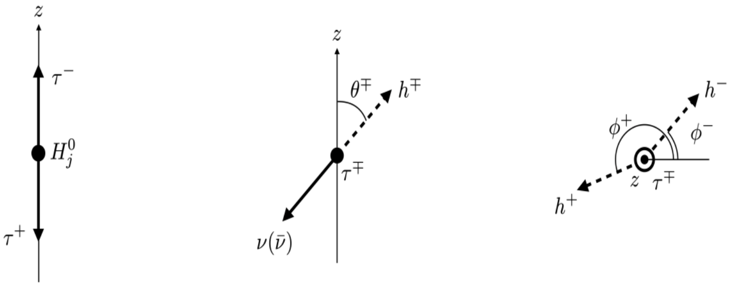


Figure: Construction of the angle Φ^*_{CP}

$$\Phi^*_{CP} = \Delta(\phi^+, \phi^-) \tag{9}$$

Using the $H \to \tau\tau$ spin-density matrix and the SM density matrix of polarized $\tau \to \pi\nu$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Phi^*_{CP}} = \frac{1}{2\pi}[1 - \frac{\pi^2}{16}(c_1 \cos\Phi^*_{CP} + c_2 \sin\Phi^*_{CP})] \tag{10}$$

$$\begin{aligned} c_1 &= \frac{a_\tau^2\beta - b_\tau^2}{a_\tau^2\beta + b_\tau^2} = \cos\phi' \\ c_2 &= -\frac{2a_\tau b_\tau \beta}{a_\tau^2\beta + b_\tau^2} = \sin\phi' \end{aligned} \tag{11}$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Phi^*_{CP}} = \frac{1}{2\pi}[1 - \frac{\pi^2}{16}(\cos\Phi^*_{CP} - \phi')] \tag{12}$$

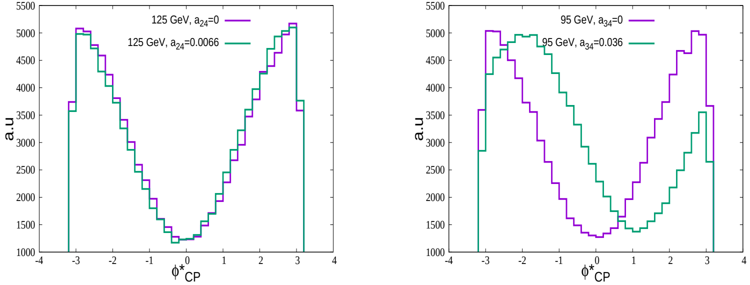
On the other hand,

$$\cos\phi_\tau = \frac{a_\tau}{\sqrt{a_\tau^2 + b_\tau^2}} \sin\phi_\tau = \frac{b_\tau}{\sqrt{a_\tau^2 + b_\tau^2}} \tag{13}$$

By comparing Eq. 12 and 14, in the limit $\beta_\tau \to 1$, $\phi' = 2\phi_\tau$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Phi^*_{CP}} = \frac{1}{2\pi}[1 - \frac{\pi^2}{16}(\cos\Phi^*_{CP} - 2\phi_\tau)] \tag{14}$$

Angular distributions



Blue → CP-even, Green → CP-mixed. The difference between the minima(maxima) of the two curves is equal to $2\phi_\tau$.

Forward-backward asymmetry

$$A_{FB} = \int_0^\pi \frac{d\sigma}{d\phi^*_{CP}} - \int_{-\pi}^0 \frac{d\sigma}{d\phi^*_{CP}} \tag{15}$$

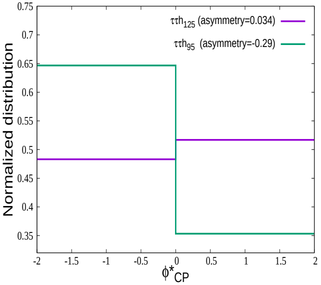


Figure: Φ^*_{CP} distribution (2-bin) for 95 GeV and 125 GeV scalars at e^+e^- collider, $\sqrt{s} = 250$ GeV, $\int \mathcal{L}dt = 5.6$ ab^{-1}. $a_{34} = 0.0356523$ and $a_{24} = 0.00662652$.

Measurement of the CP-violating phase for h_{95}

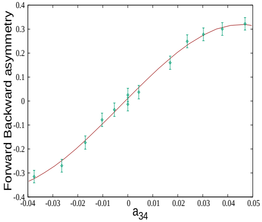


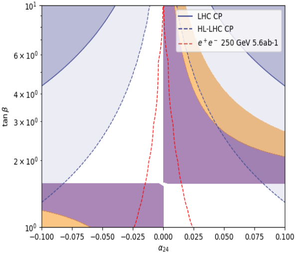
Figure: forward-backward asymmetry as a function of a_{34}.

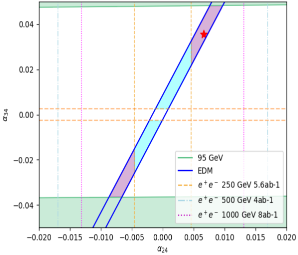
The error in asymmetry mesaurement can be expressed as $\sigma_A = \sqrt{\frac{1-A^2}{N_{events}}}$

$$\chi^2 = \sum_i \frac{(A_i^{measured} - A_i(a_{34}))^2}{\sigma_{A_i}^2} \tag{16}$$

$$\sigma_{34}^{-2} = \sum_i \frac{1}{\sigma_{A_i}^2} \frac{dA_i}{da_{34}} \tag{17}$$

Summary Plots





- If $a_{24} \gtrsim 0.005$, CP-violation in 125 GeV Higgs can be observed at 250 GeV e^+e^- machine.
- If CPV is observed in the 125 GeV Higgs, and no EDM, it would unequivocally indicate presence of additional sources of CPV in the extended scalars, since $a_{24} \lesssim 0.0006$, when no other source is present.
- The purple regions are where both h_{95} CP phase and h_{125} CP-phase can be detected, the cyan regions are where h_{125} CPV is not detectable while h_{95} can be detected.

Summary

- Our goal in this work here, is to probe CP-violation at the future e^+e^- collider.
- A 250 GeV e^+e^- collider will be able to pin-down the CP-mixing in the 125 GeV with unprecedented precision. However, an observation of a CP-phase will be in tension with EDM data.
- An additional source of CPV in an extra scalar can be an exciting prospect.
- In this light, we explore the CPV in the 95 GeV excess, which is consistent with the excess, as well satisfy the EDM bounds.
- If the excess is confirmed in the future, its CP-properties will also be precisely probed at a 250 GeV e^+e^- collider.
- In our analysis, only hadronic decay mode of the tau leptons are considered and leptonic decay mode of Z boson. A full reconstruction of ρ or a_1 mason is assumed from its 2-body or 3-body pion decay final states.

Thank You

Questions

- Explanation of the left panel.
- Why is 1 TeV ILC better than 500 GeV ILC for 125 GeV CPV?
- A comparison with LHC and HL-LHC and ILC for 125 GeV Higgs, (we had an older plot), may be good for the audience to appreciate the ILC precision in this context.
- Baryogenesis plot in the back-up may be if someone asks?
- 150 GeV low mass scalar is allowed from constraints because of no mixing with the doublet states, right?
- M^2_{H24} and M^2_{H34} have different complex parameters and therefore, the source of CPV in 95 GeV and 125 GeV are different?