

Multi-photon signatures at LHC (and ILC) as a probe of CP-Violation in 2HDMs

Kento Katayama

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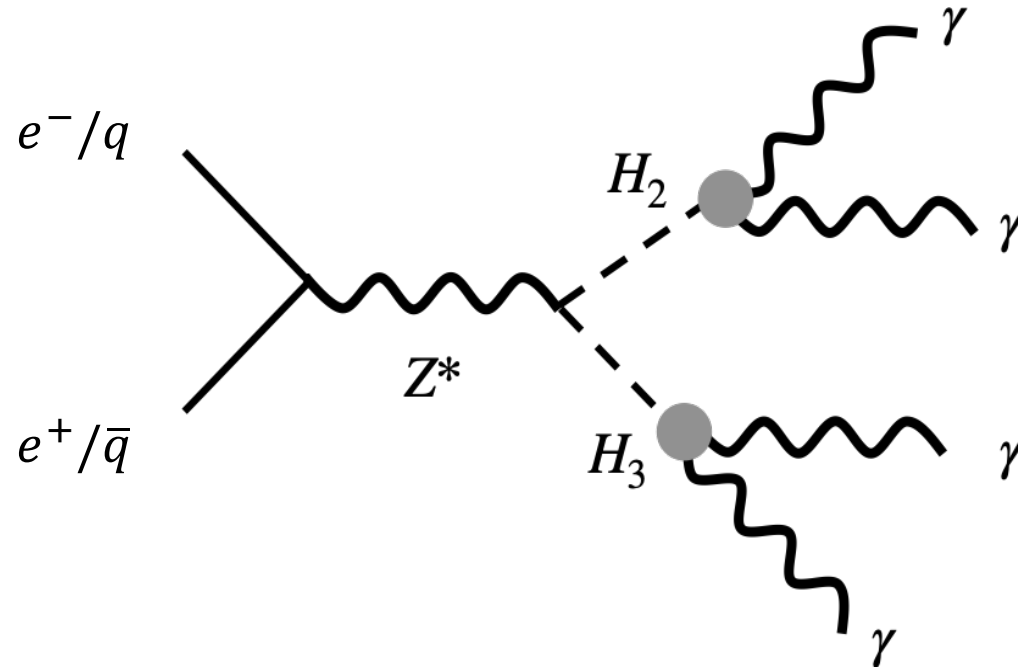
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(Paper in preparation)

HPNP2023@Osaka U. Jun. 6th, 2023

$$pp/e^+e^- \rightarrow Z^* \rightarrow H_2H_3 \rightarrow 4\gamma$$



Multi-photon signatures are good for detecting the CP-violation in Aligned Two Higgs Doublet Model (A2HDM) .

Aligned Two Higgs Doublet Model (A2HDM)

- New CP-violations (CPV) appear in the Yukawa interaction and the potential.
- Electroweak baryogenesis (EWBG) \rightarrow The baryon asymmetry of the universe (BAU) is explained.
- The Electric Dipole Moment (EDM) \rightarrow Parameters are strongly constrained.

Electron EDM (eEDM) : $|d_e| < 4.1 \times 10^{-30} e \text{ cm}$ (90%CL) [T. S. Roussy, et al., 2022]

A2HDM { The destructive interference in the eEDM [S. Kanemura, et al., 2020]
 $d_e = d_e(\text{Higgs}) + d_e(\text{fermion})$ \rightarrow CPV phase $\sim \mathcal{O}(1)$
The destructive interference
EWBG with the destructive interference [K. Enomoto, et al., 2022]

The quantity and property of CPV are important .

Outline

- Introduction
- A2HDM
- Multi-photon signatures at LHC and future linear colliders
- Summary

The potential in the Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{v + H_1 + iG^0}{\sqrt{2}} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{H_2 + iH_3}{\sqrt{2}} \end{pmatrix}$$

$$V = -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \{\mu_3^2(\Phi_1^\dagger\Phi_2) + \text{h.c.}\} \\ + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ + \left\{ \left[\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2) + \lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2) \right] (\Phi_1^\dagger\Phi_2) + \text{h.c.} \right\}$$

- Stationary condition $\mu_1^2 = \frac{1}{2}\lambda_1 v^2, \mu_3^2 = \frac{1}{2}\lambda_6 v^2$
- Charged Higgs mass $H^\pm: m_{H^\pm}^2 = -\mu_2^2 + \frac{1}{2}\lambda_3 v^2$
- Mass matrix of neutral Higgs

\bigcirc : the complex parameter

$$\mathcal{M}_{ij} = v^2 \begin{pmatrix} \lambda_1 & \Re\lambda_6 & -\Im\lambda_6 \\ \Re\lambda_6 & -\frac{\mu^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + \Re\lambda_5) & -\frac{1}{2}\Im\lambda_5 \\ -\Im\lambda_6 & -\frac{1}{2}\Im\lambda_5 & -\frac{\mu^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - \Re\lambda_5) \end{pmatrix}$$

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○ : the complex parameter

The redefinition of Φ_1, Φ_2

$$(\Phi_1^\dagger\Phi_2) \rightarrow e^{-i\frac{\arg\lambda_5}{2}}(\Phi_1^\dagger\Phi_2)$$

$$\mathcal{M}_{ij} = v^2 \begin{pmatrix} \lambda_1 & \cancel{\Re\lambda_6} & \cancel{-\Im\lambda_6} \\ \cancel{\Re\lambda_6} & -\frac{\mu^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + \Re\lambda_5) & \cancel{-\frac{1}{2}\Im\lambda_5} \\ \cancel{-\Im\lambda_6} & \cancel{-\frac{1}{2}\Im\lambda_5} & -\frac{\mu^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - \Re\lambda_5) \end{pmatrix}$$

Higgs alignment

$$\lambda_6 = 0$$

This is favored by the current LHC data.

The potential in the Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{v + H_1 + iG^0}{\sqrt{2}} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{H_2 + iH_3}{\sqrt{2}} \end{pmatrix}$$

$$V = -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \{\mu_3^2(\Phi_1^\dagger\Phi_2) + \text{h.c.}\} \\ + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ + \left\{ \left[\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2) + \lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2) \right] (\Phi_1^\dagger\Phi_2) + \text{h.c.} \right\}$$

- Stationary condition $\mu_1^2 = \frac{1}{2}\lambda_1 v^2, \mu_3^2 = \frac{1}{2}\lambda_6 v^2$
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- Mass matrix of neutral Higgs

$$H_1: m_{H_1}^2 = \lambda_1 v^2 \text{ (SM Higgs)}$$

$$H_2: m_{H_2}^2 = -\mu_2^2 + \frac{1}{2}v^2(\lambda_3 + \lambda_4 + \Re\lambda_5)$$

$$H_3: m_{H_3}^2 = -\mu_2^2 + \frac{1}{2}v^2(\lambda_3 + \lambda_4 - \Re\lambda_5)$$

\bigcirc : the complex parameter

7 real free parameters

$$\mu_2^2, m_{H_2}, m_{H_3}, m_{H^\pm}, \lambda_2, |\lambda_7|$$

$$\theta_7 (= \arg\lambda_7)$$

Yukawa interaction


$$\mathcal{L}_{\text{Yukawa}} = -\overline{Q}_L^u \left(\sqrt{2} \frac{M_u}{v} \tilde{\Phi}_1 + \rho_u \tilde{\Phi}_2 \right) u_R - \overline{Q}_L^d \left(\sqrt{2} \frac{M_d}{v} \Phi_1 + \rho_d \Phi_2 \right) d_R \\ - \overline{L}_L \left(\sqrt{2} \frac{M_e}{v} \Phi_1 + \rho_e \Phi_2 \right) e_R + \text{h. c.}$$

- $\rho_{u,d,e}$ are 3×3 complex matrices.  Flavor Changing Neutral Current (FCNC) appears at tree level.

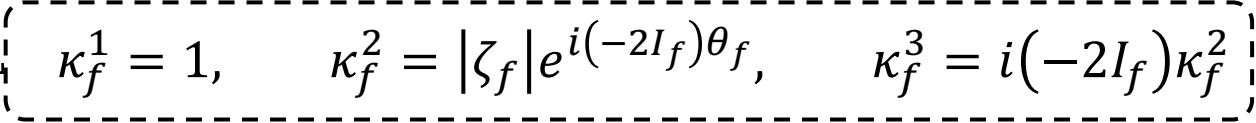
- To avoid FCNC at tree level, we assume the “Yukawa alignment”.

[A. Pich, et al. 2009] 

$$\rho_u = \zeta_u^* \frac{M_u}{v}, \\ \rho_{d,e} = \zeta_{d,e} \frac{M_{d,e}}{v}$$



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


 $\left[\kappa_f^1 = 1, \quad \kappa_f^2 = |\zeta_f| e^{i(-2I_f)\theta_f}, \quad \kappa_f^3 = i(-2I_f)\kappa_f^2 \right]$

Gauge interaction

$$R^T \mathcal{M} R = \text{diag}(m_{H_1}^2, m_{H_2}^2, m_{H_2}^2)$$

$$\mathcal{L}_{\text{kin}} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2 = \dots + \sum_{j=1}^3 R_{1j} \left(\frac{2m_W^2}{v} W_\mu W^\mu + \frac{m_Z^2}{v} Z_\mu Z^\mu \right) H_j + \dots$$

When $\lambda_6 = 0$ (Higgs alignment), $R_{ij} = \delta_{ij}$



- $H_1 VV$ are the same as those of the SM. ($V = W, Z$)
- $H_2 VV, H_3 VV$ vanish at tree level.

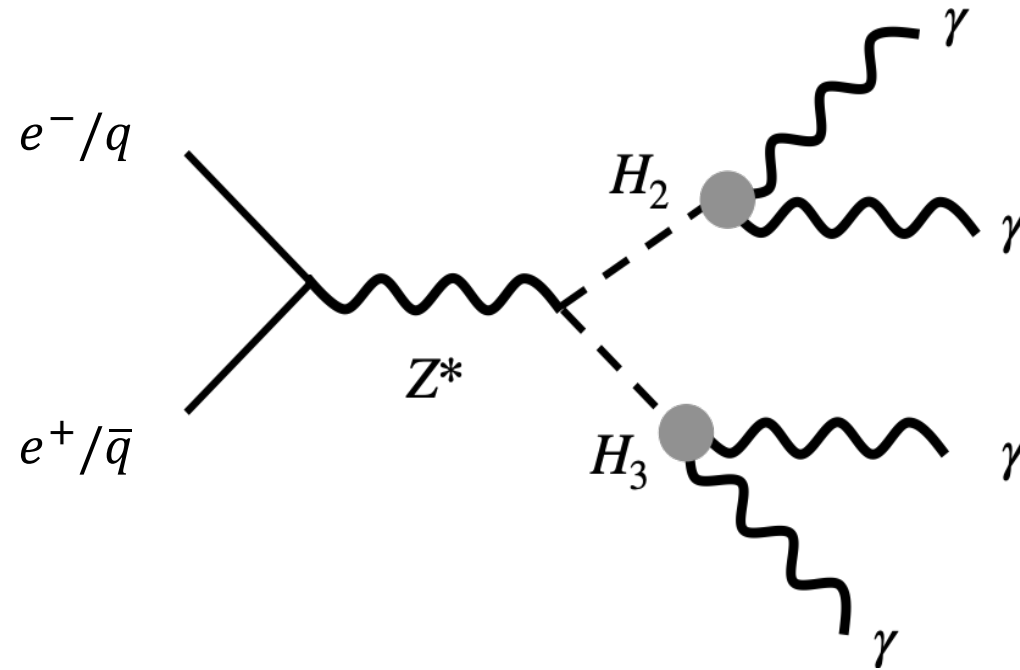
Summary of real free parameters

potential	$\mu_2^2, m_{H_2}, m_{H_3}, m_{H^\pm}, \lambda_2, \lambda_7 $	θ_7
Yukawa	$ \zeta_u , \zeta_d , \zeta_e $	$\theta_u, \theta_d, \theta_e$

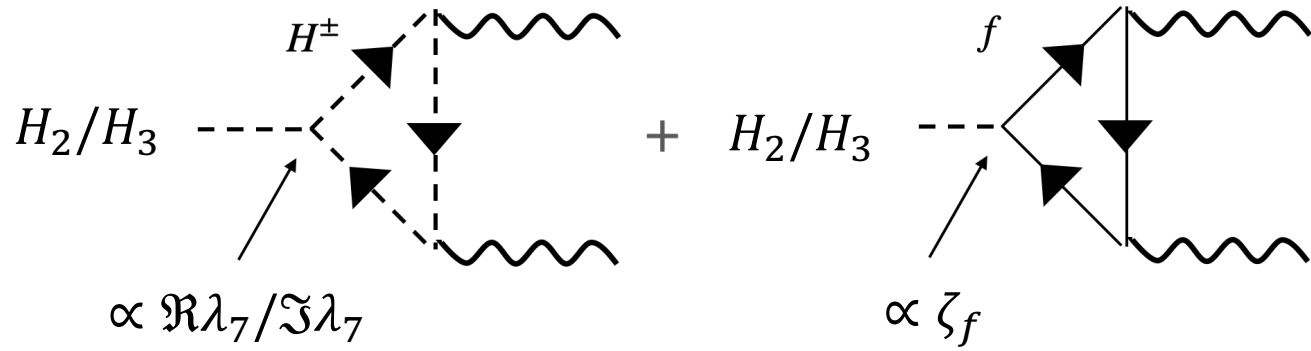
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$$pp/e^+e^- \rightarrow Z^* \rightarrow H_2H_3 \rightarrow 4\gamma$$

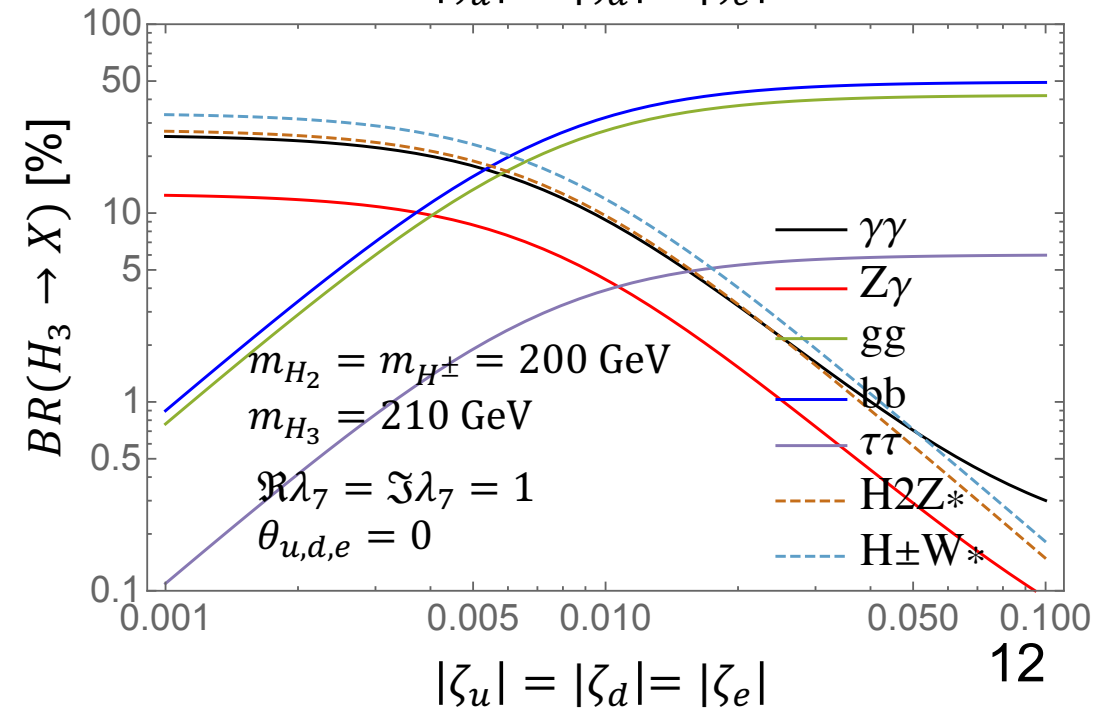
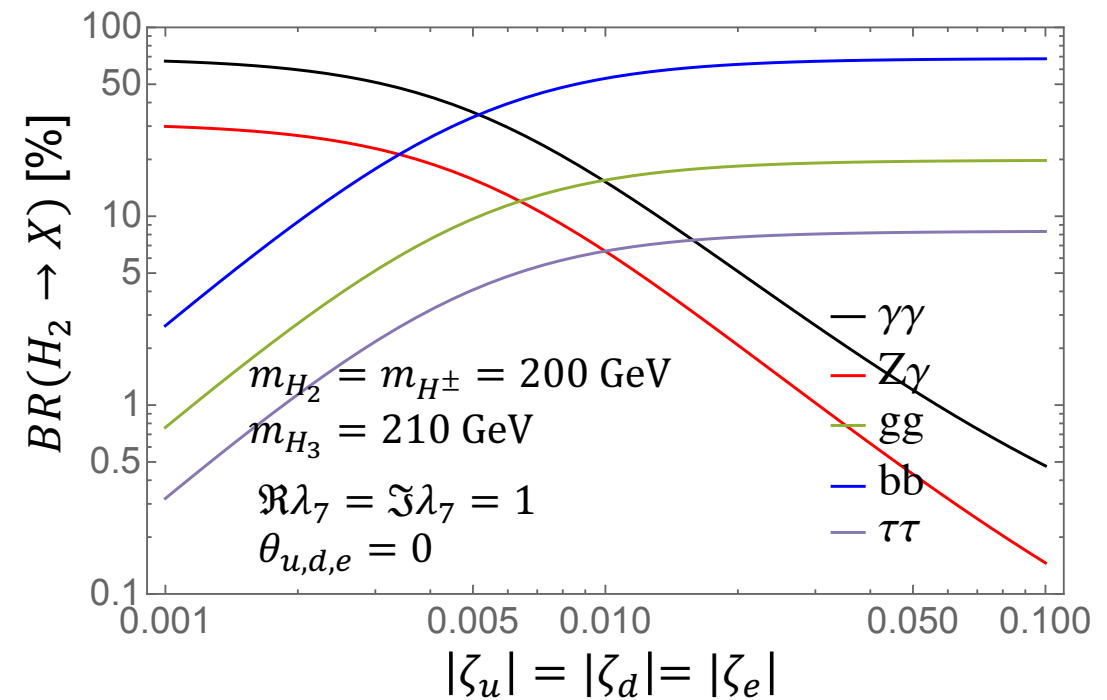


$\gamma\gamma/Z\gamma$ decays of H_2/H_3



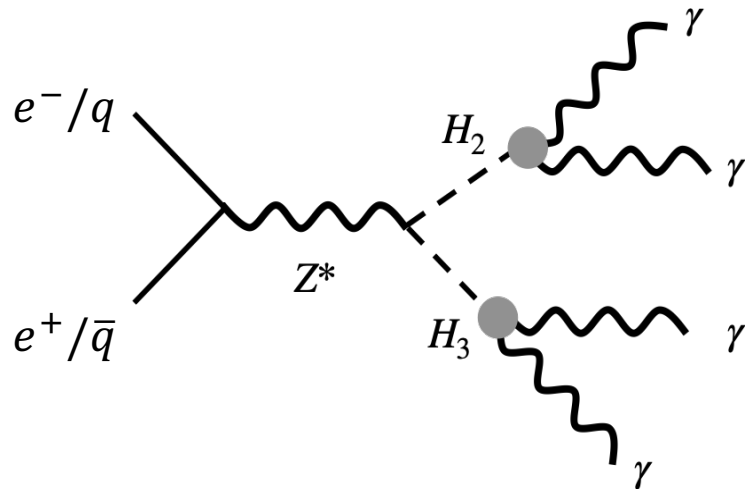
- $\gamma\gamma/Z\gamma$ decays are induced by charged Higgs and fermions at loop level.
 - The fermiophobic scenario ($|\zeta_{u,e,d}| \ll 1$) and $m_{H_2,H_3} < 2m_t$
- ➔ $\gamma\gamma/Z\gamma$ decays compete with other decay channels.

Hereafter, we consider $|\zeta_{u,e,d}| \ll 1$ and $m_{H_2,H_3} < 2m_t$.



The multi-photon signature

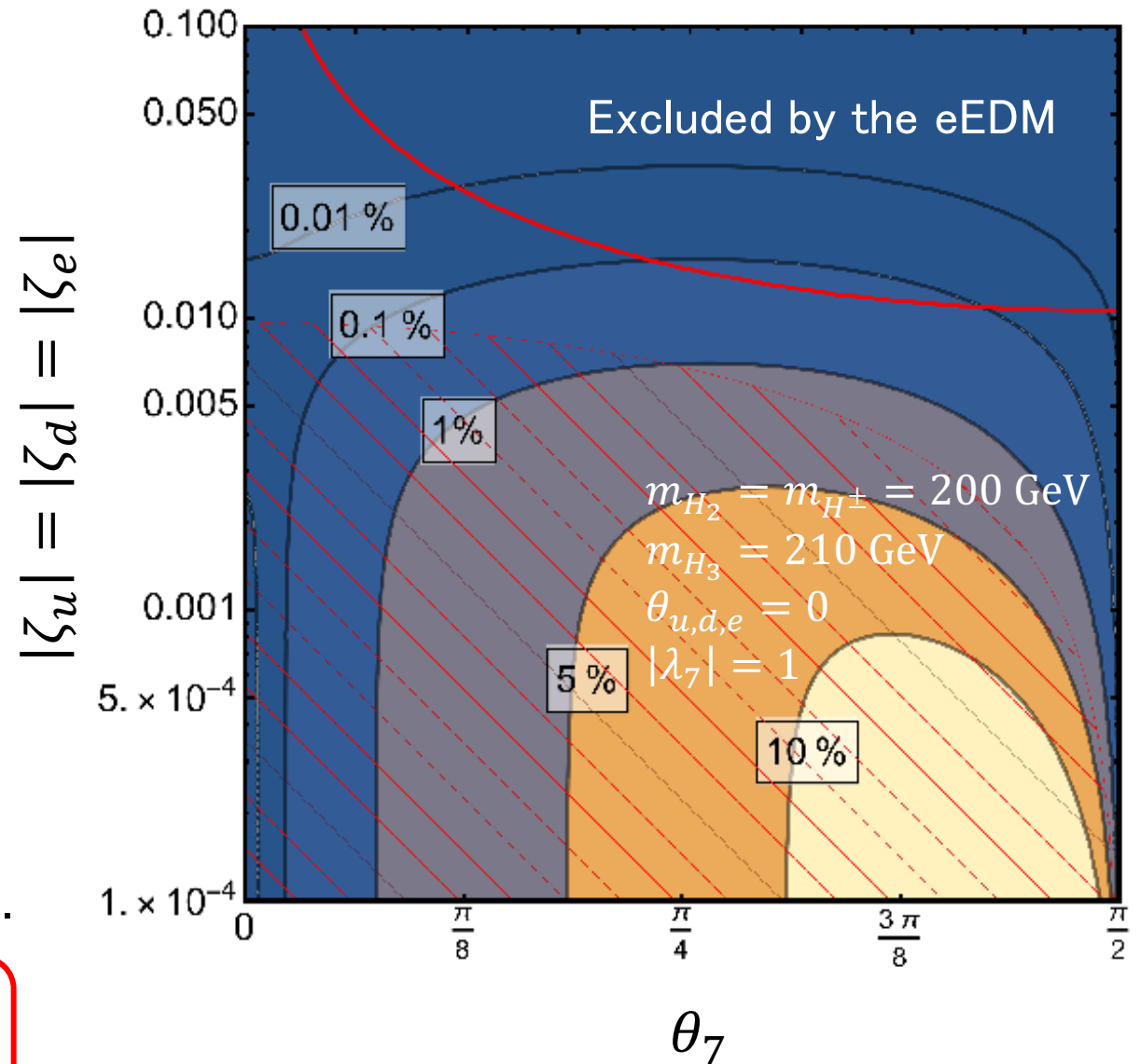
$$pp/e^+e^- \rightarrow Z^* \rightarrow H_2H_3 \rightarrow 4\gamma$$



- The background can be negligible.
- CP-conservation in the potential ($\theta_7 = 0$)
 - The charged Higgs loop for H_3 vanishes.
 - $BR(H_2 \rightarrow \gamma\gamma) \times BR(H_3 \rightarrow \gamma\gamma)$ is very small.

This signal can be the evidence of the CPV of the potential in A2HDM.

$$BR(H_2 \rightarrow \gamma\gamma) \times BR(H_3 \rightarrow \gamma\gamma) [\%]$$



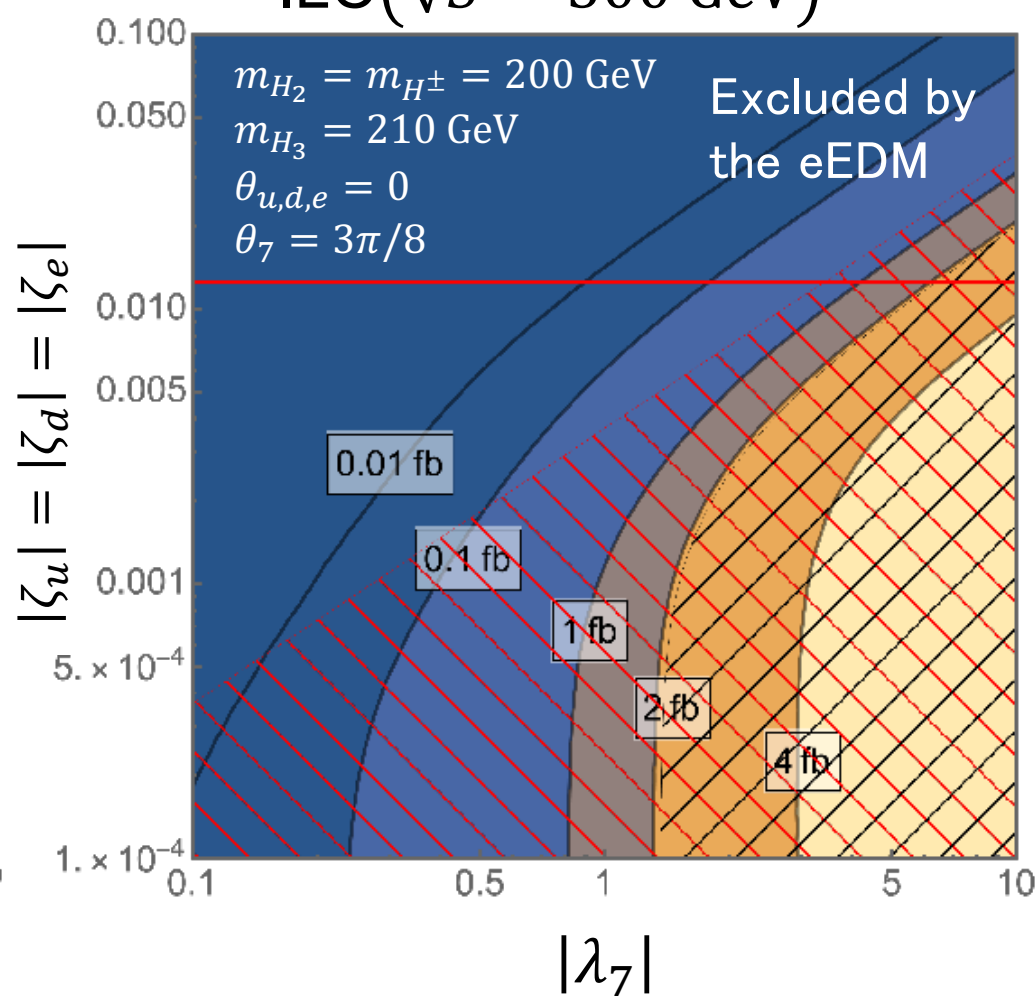
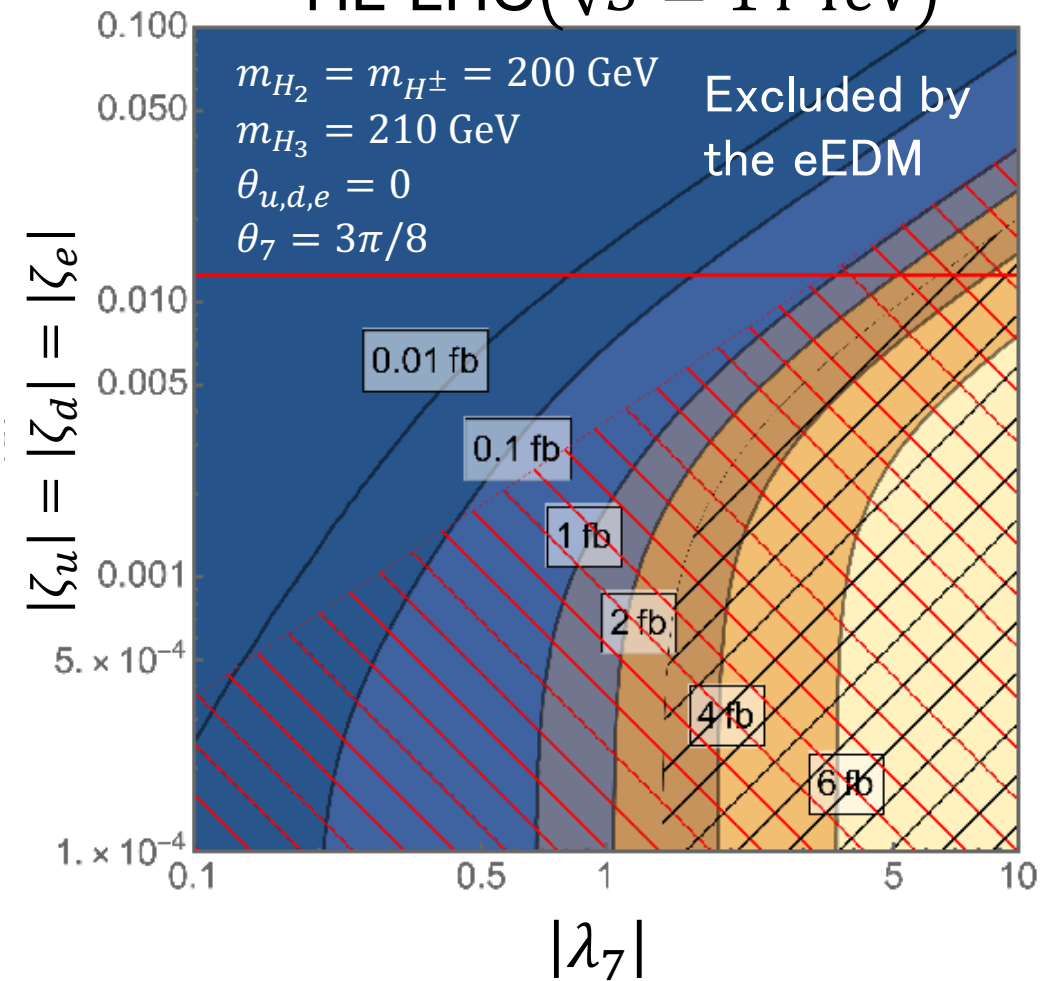
di-photon search

[ATLAS. 2021]


The cross section of $pp/e^+e^- \rightarrow Z^* \rightarrow H_2H_3 \rightarrow 4\gamma$


HL-LHC ($\sqrt{S} = 14$ TeV)

ILC ($\sqrt{S} = 500$ GeV)



Excluded by LHC


 $3\gamma + X,$
 8 TeV 20 fb $^{-1}$,
 $pp \rightarrow H_2H_3 \rightarrow 4\gamma$
[\[ATLAS. 2016\]](#)


di-photon search
[\[ATLAS. 2021\]](#)

$|\lambda_7| \sim 1, |\zeta_{u,d,e}| \sim 10^{-2} \rightarrow$ Event # ~ 300 ($\mathcal{L} = 3000$ fb $^{-1}$)

Summery

- In A2HDM, new CPVs appear in the Yukawa interaction and the potential.
- A2HDM can explain the BAU by EWBG with the destructive interference in the eEDM.
- $\gamma\gamma/Z\gamma$ decays of H_2/H_3 compete with other decay channels when the fermiophobic scenario $|\zeta_{u,e,d}| \ll 1$ and $m_{H_2,H_3} < 2m_t$.
- ◆ $pp/e^+e^- \rightarrow Z^* \rightarrow H_2H_3 \rightarrow 4\gamma$
 - This signal can be the evidence of the CPV of the potential in A2HDM.
 - This signal can be detected not only in HL-LHC but also in ILC.

Back up

- When the mass matrix \mathcal{M}_{ij} is not diagonalized,

$$R_{ij} \neq \delta_{ij}$$

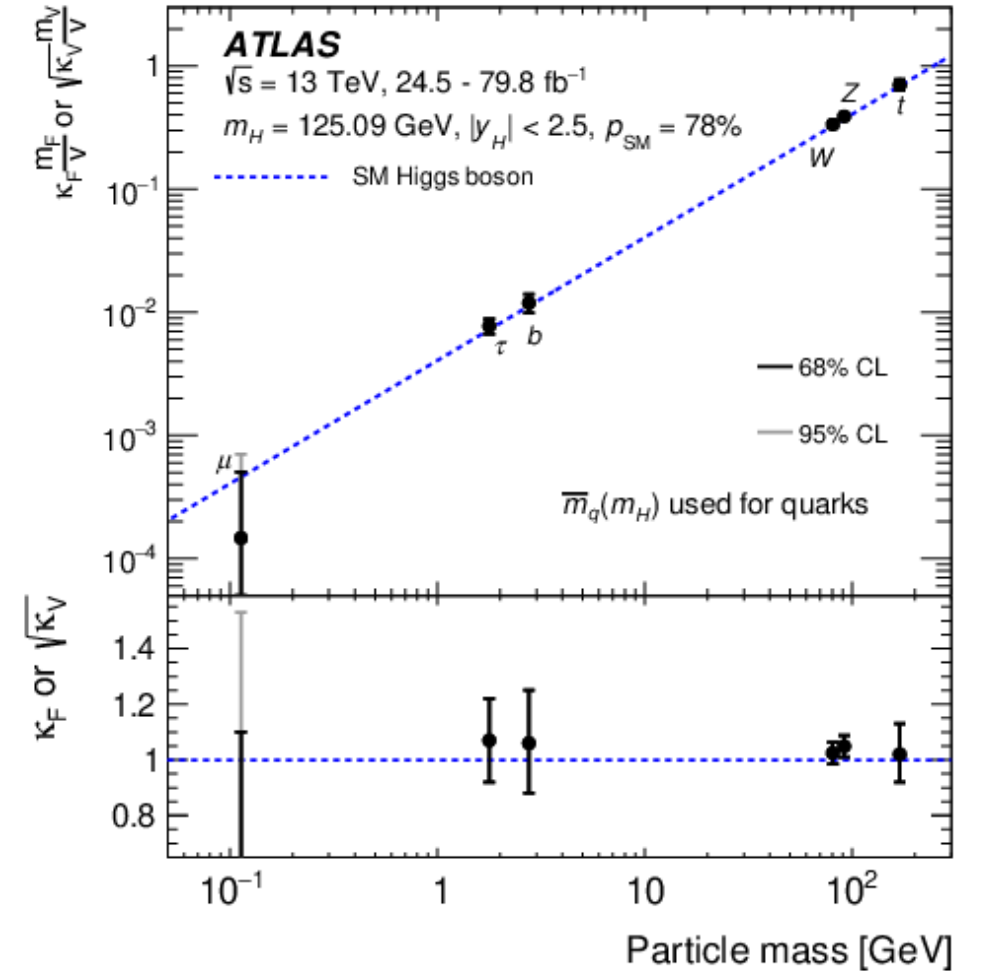
$$\mathcal{L}_{\text{kin}} = \dots + \sum_{j=1}^3 R_{1j} \left(\frac{2m_W^2}{v} W_\mu W^\mu + \frac{m_Z^2}{v} Z_\mu Z^\mu \right) H_j + \dots$$

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

$$\kappa_f^j = R_{1j} + \{R_{2j} + i(-2I_f)R_{3j}\} |\zeta_f| e^{i(-2I_f)\theta_f}$$

The tree-level induced deviation of the coupling constants of the 125 GeV Higgs boson from its SM prediction

- When mass matrix \mathcal{M}_{ij} is diagonalized (Higgs alignment), interactions of H_1 are the same as those of the SM.



[ATLAS, 2020]

The detractive interference in the eEDM

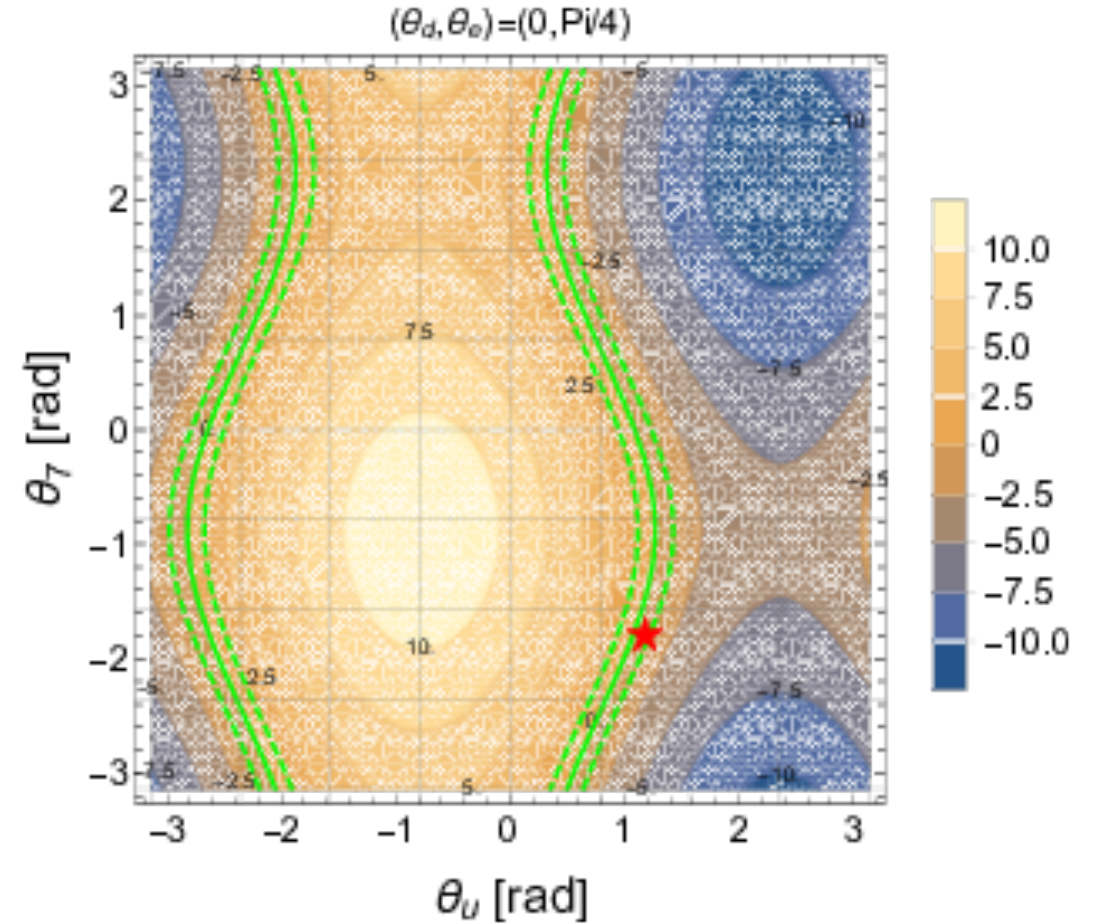
$$d_e = d_e(\text{Higgs}) + d_e(\text{fermion})$$



Requiring the detractive interference b/w $d_e(\text{Higgs})$ and $d_e(\text{fermion})$ in order to $d_e \cong 0$,

$$\rightarrow |\zeta_u| \sin(\theta_u - \theta_e) \propto |\lambda_7| \sin(\theta_7 - \theta_e)$$

(When $\theta_d = 0$)



[S. Kanemura, et al., 2020]

$$\star (\theta_7, \theta_u) = (1.2, -1.8)$$

$$m_{H_2} = 280, m_{H^\pm} = 230,$$

$$|\lambda_7| = 0.3, |\zeta_u| = 10^{-2},$$

$$|\zeta_d| = 0.1, |\zeta_d| = 0.5$$

$BR(H_3 \rightarrow X)$

