Multi-photon signatures at LHC and future linear colliders as a probe of CP-Violation in 2HDMs

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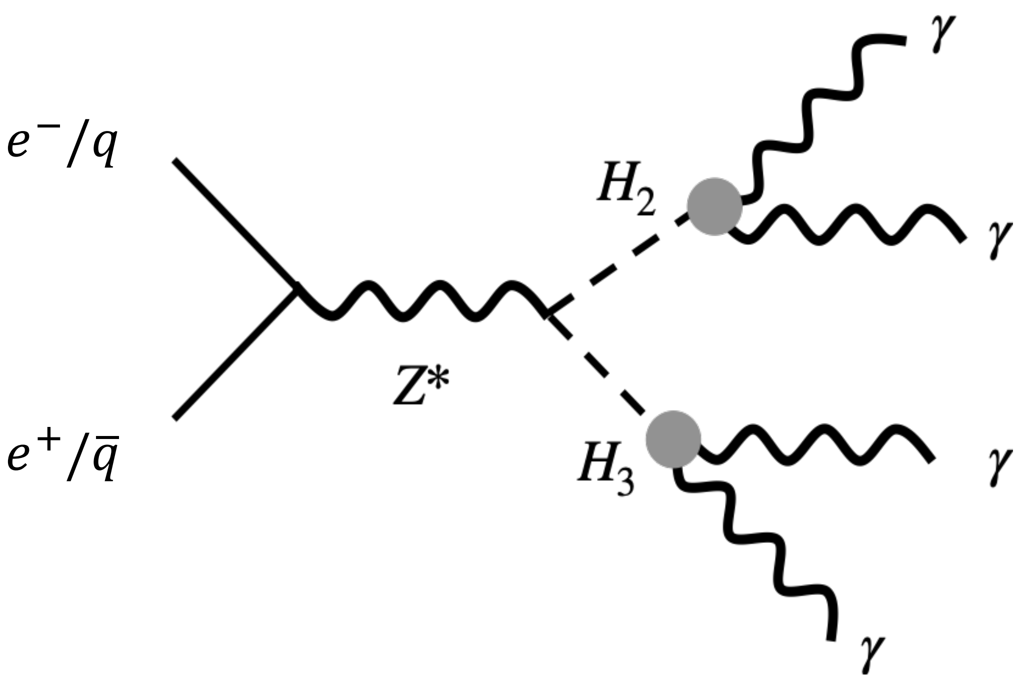
$$pp/e^+e^- \to Z^* \to H_2H_3 \to 4\gamma$$



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) → The baryon asymmetry of the universe (BAU) is explained.
- The Electric Dipole Moment (EDM) → Parameters are strongly constrained.

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

A2HDM

- The destructive interference in the eEDM [S. Kanemura, et al., 2020]

  $d_e = d_e(\mathrm{Higgs}) + d_e(\mathrm{fermion})$ → CPV phase ~ $\mathcal{O}(1)$

  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

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

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

: the complex parameter

- 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 $H^\pm\!:\ m_{H^\pm} = -\mu_2^2 + \frac{1}{2}\lambda_3 v^2$
- Mass matrix of neutral Higgs

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

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The redefinition of Φ_1, Φ_2

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

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

Higgs alignment

$\lambda_6 = 0$

This is favored by the current LHC data.

The potential in the Higgs basis

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: the complex parameter

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- Charged Higgs mass $H^\pm$: $m_{H^\pm} = -\mu_2^2 + \frac{1}{2}\lambda_3 v^2$
- Mass matrix of neutral Higgs

H_1: $m_{H_1}^2 = \lambda_1 v^2$ (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: $m_{H_3}^2 = -\mu_2^2 + \frac{1}{2}v^2(\lambda_3 + \lambda_4 - \Re\lambda_5)$

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]

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

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

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

$$+\frac{\sqrt{2}}{v}\{\zeta_u\overline{u_R}M_u V_{\text{CKM}}d_L - \zeta_d\overline{u_L}V_{\text{CKM}}M_d d_R - \zeta_e\overline{\nu_L}M_e e_R\}H^+ + \text{h.c.}$$

Gauge interaction

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

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

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

- $H_1 VV$ are the same as those of the SM.
- $H_2 VV, H_3 VV$ vanish at tree level.

$(V = W, Z)$

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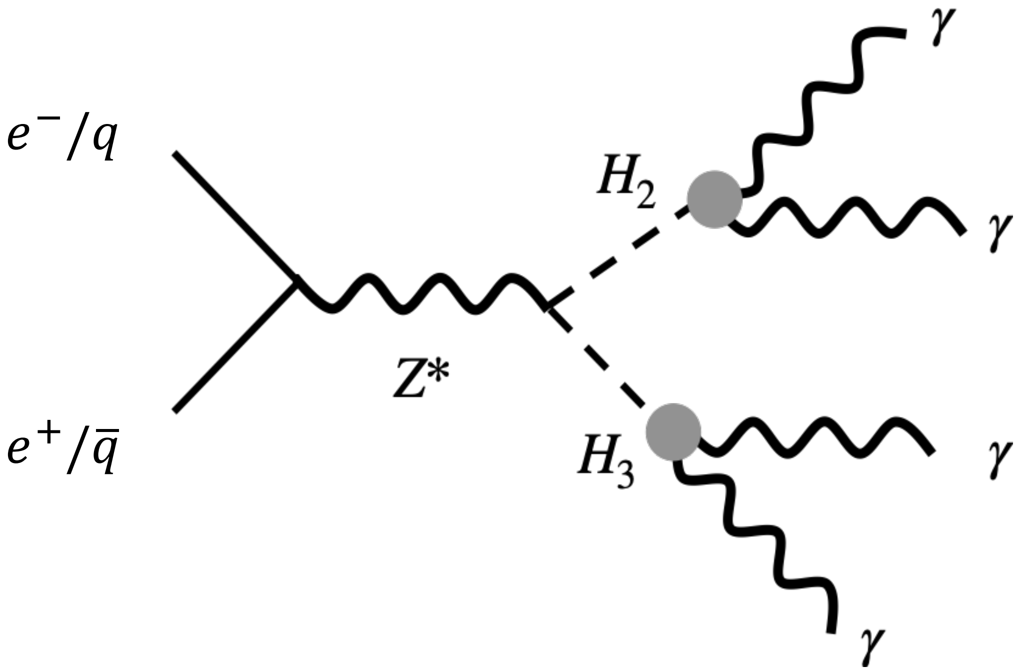
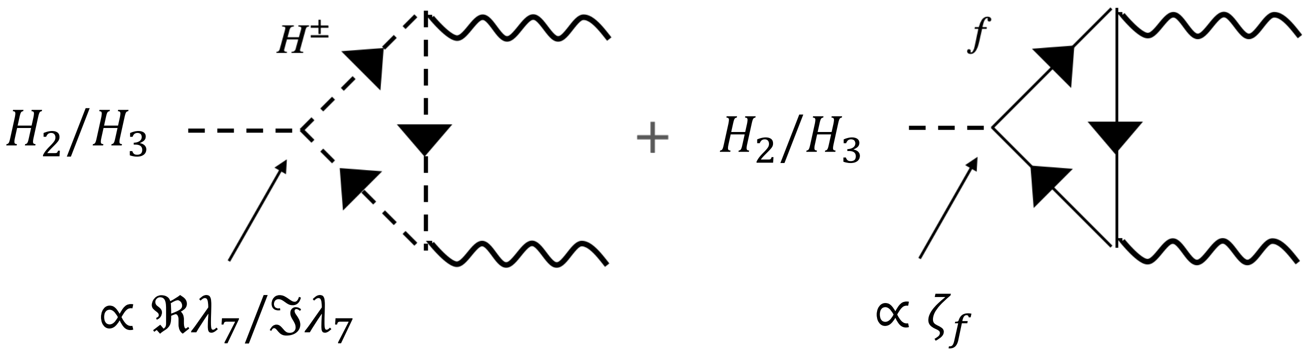
$$pp/e^+e^- \rightarrow Z^* \rightarrow H_2H_3 \rightarrow 4\gamma$$



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



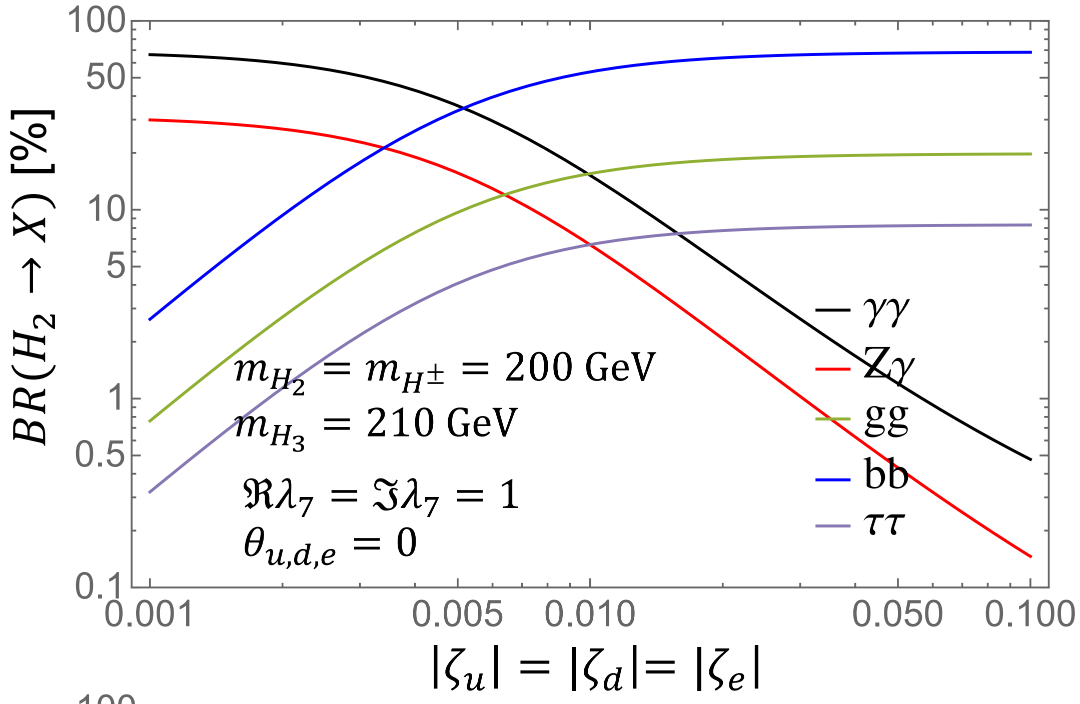
- $\gamma\gamma/Z\gamma$ decays are induced by charged Higgs and fermions at loop level.

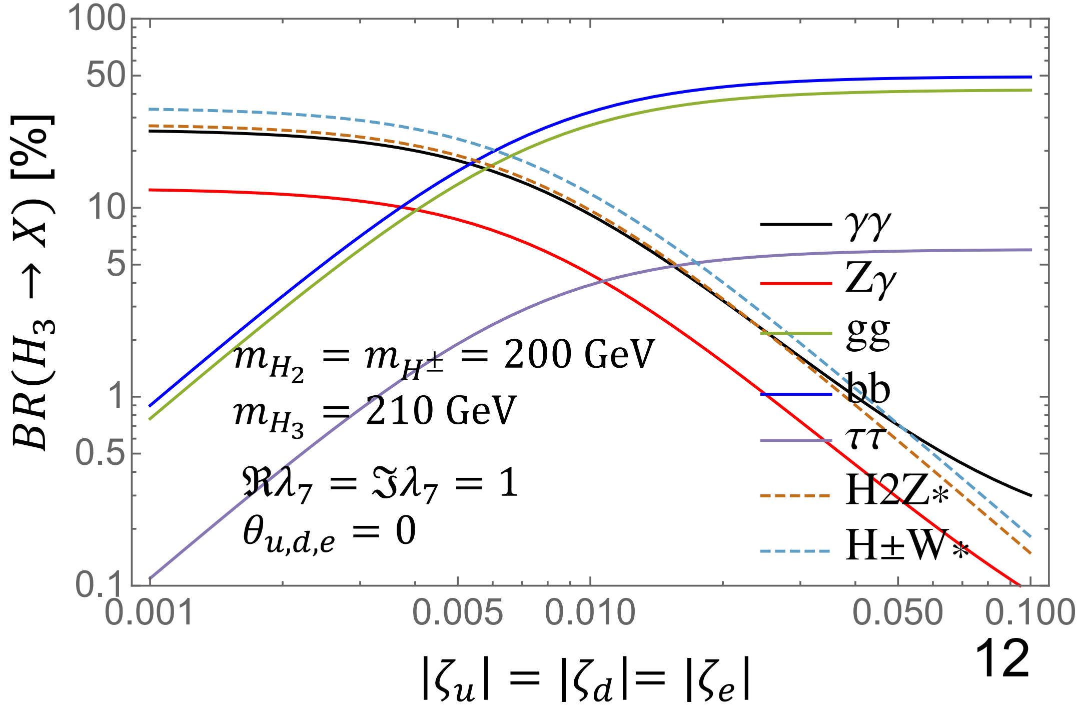
- The fermiophobic scenario $(|\zeta_{u,e,d}| \ll 1)$

  and $m_{H_2,H_3} < 2m_t$

➡ $\gamma\gamma/Z\gamma$ decays compete with other decay channels.

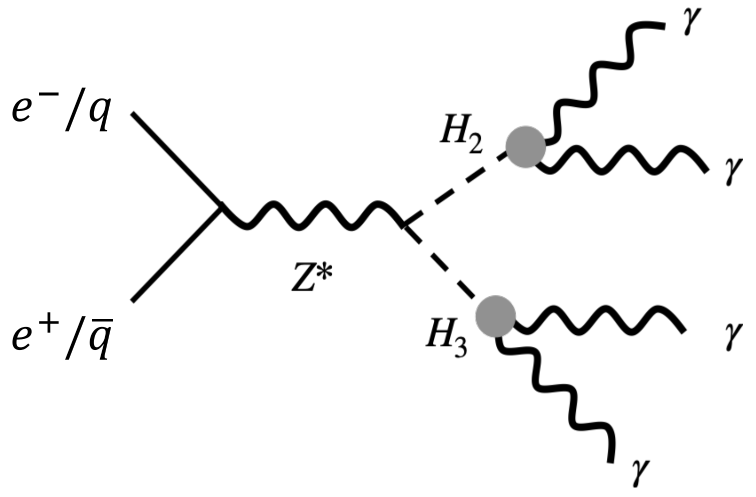
Hereafter,
we consider $|\zeta_{u,e,d}| \ll 1$ and $m_{H_2,H_3} < 2m_t$.





The multi-photon signature

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



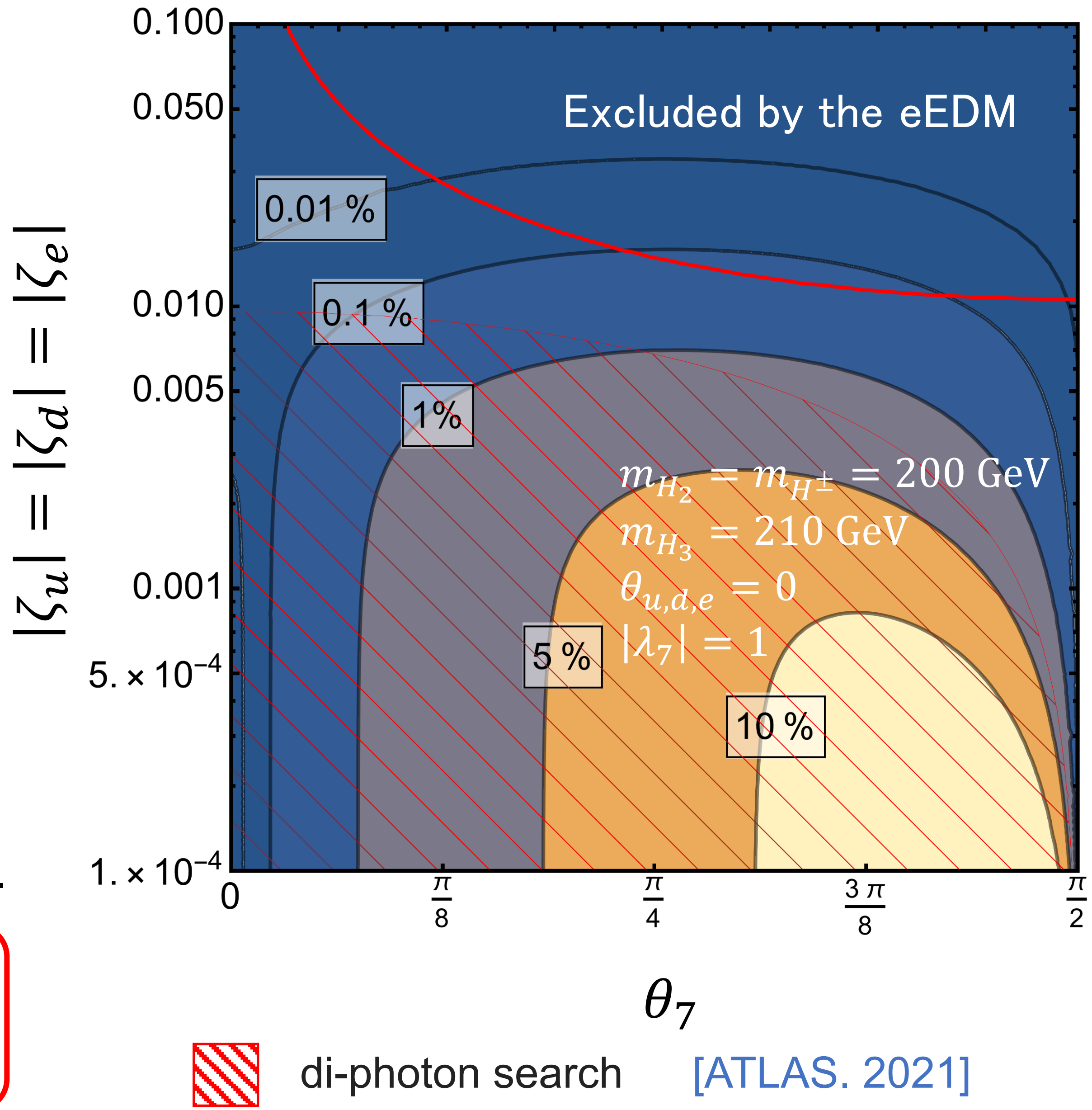
- The background can be negligible.
- CP-conservation in the potential($\theta_7 = 0$)

➡ The charged Higgs loop for H_3 vanishes.

➡ $BR(H_2 \to \gamma\gamma)\times BR(H_3 \to \gamma\gamma)$ is very small.

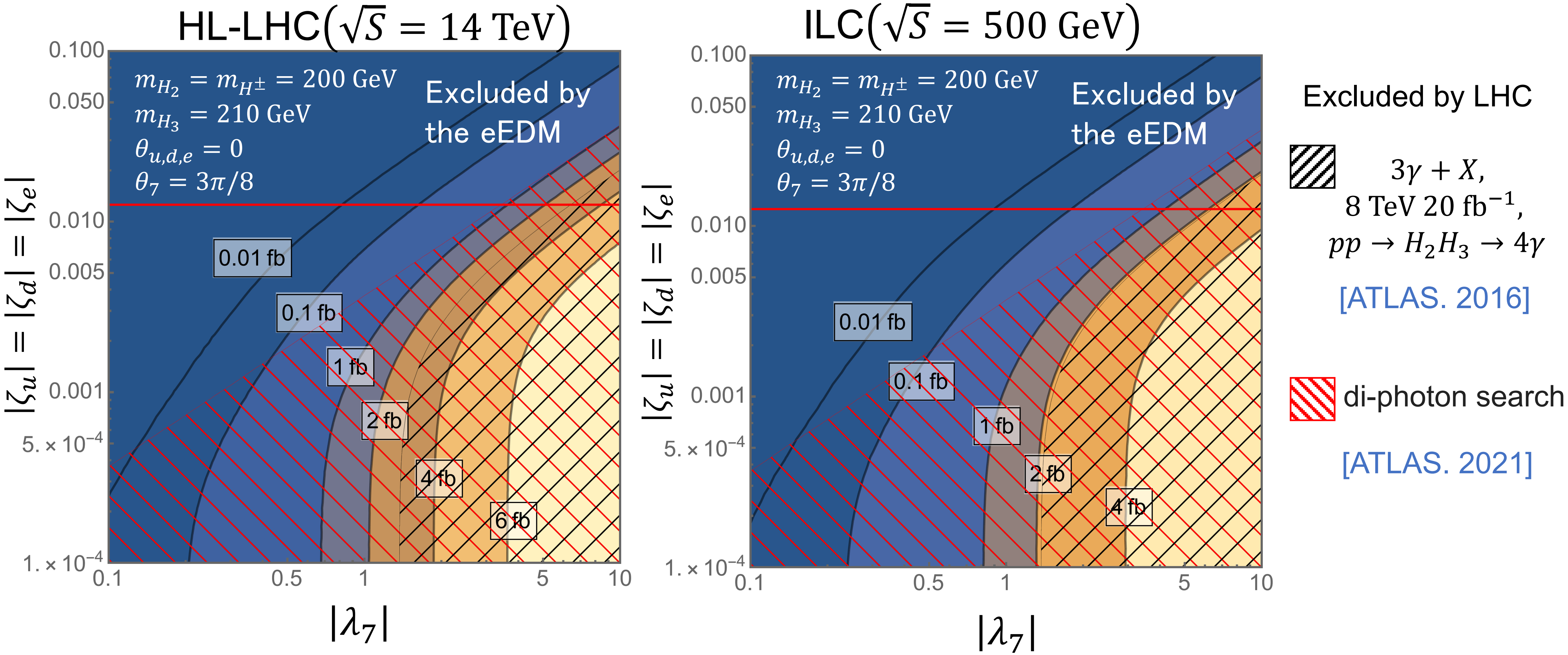
This signal can be the evidence of the CPV of the potential in A2HDM.

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



[ATLAS. 2021]

The cross section of $pp/e^+e^- \to Z^* \to H_2 H_3 \to 4\gamma$



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

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

$pp/e^+e^- \to Z^* \to H_2 H_3 \to 4\gamma$

- 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,

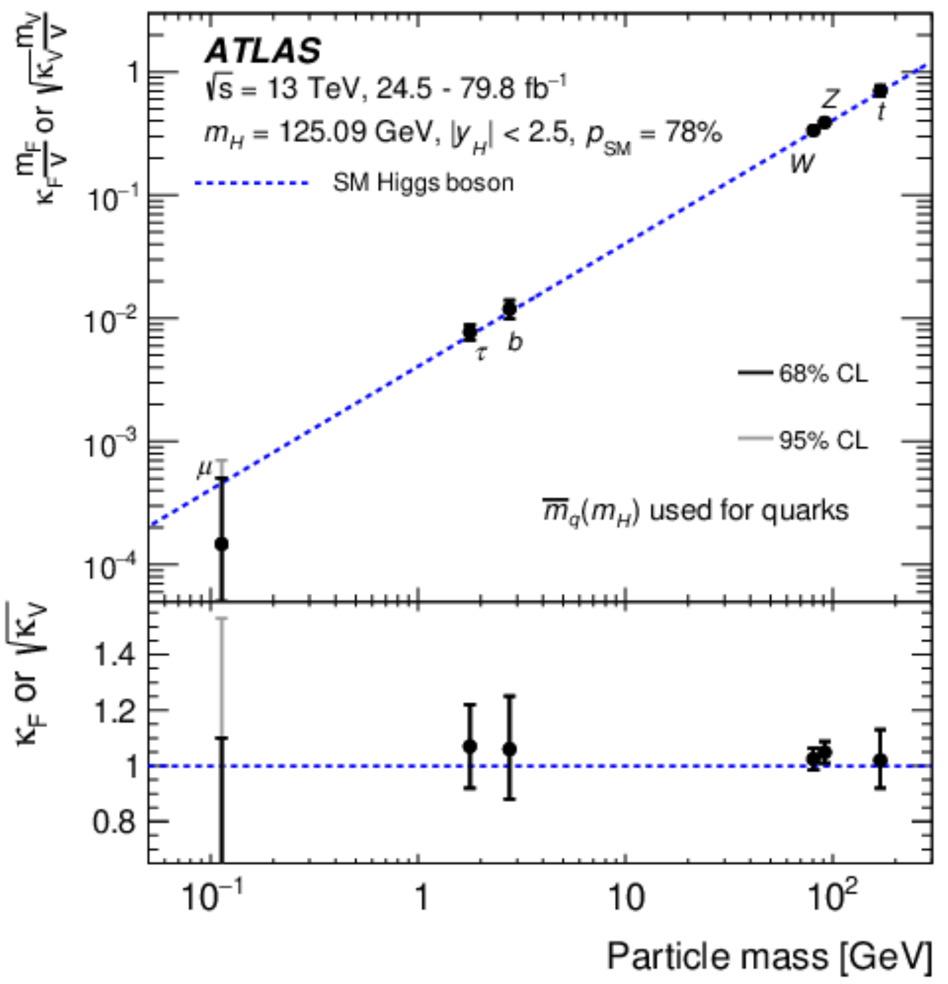
$$R_{ij} \neq \delta_{ij}$$

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

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

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

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



[ATLAS, 2020]

- When mass matrix $\mathcal{M}_{ij}$ is diagonalized (Higgs alignment),

  interactions of H_1 are the same as those of the SM.

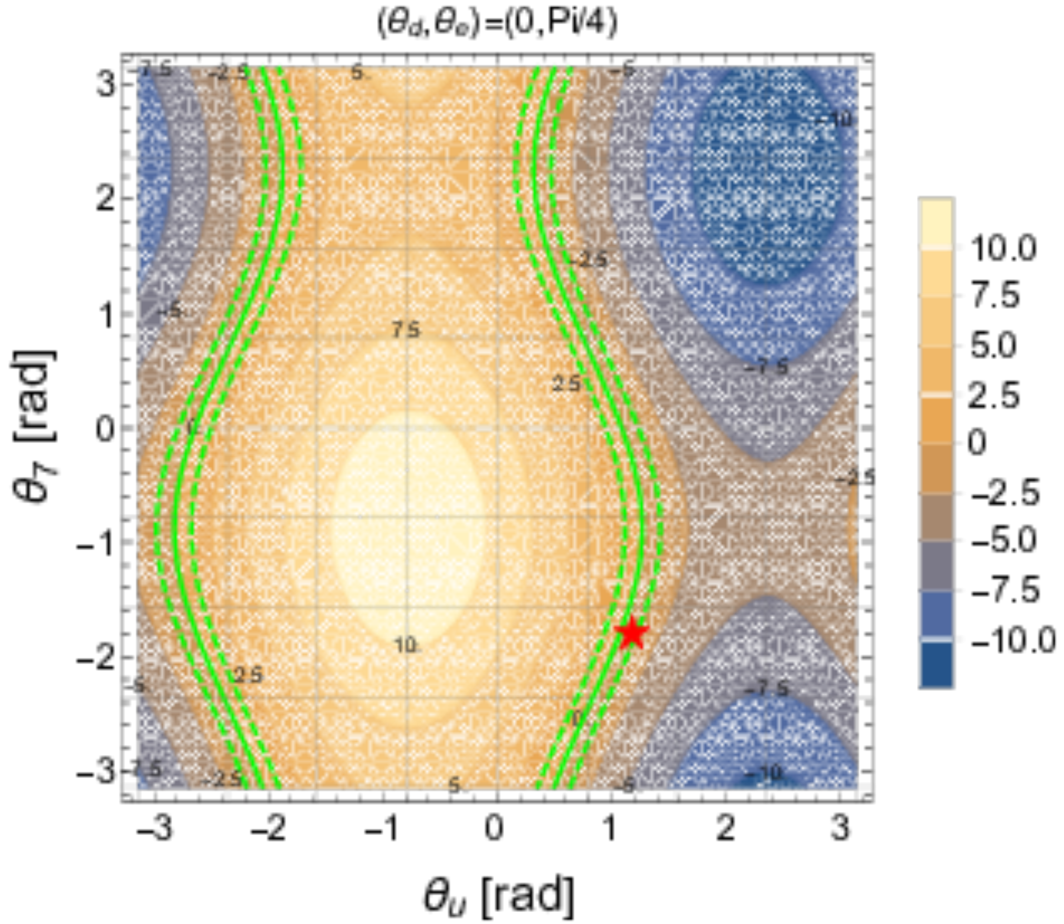
The detractive interference in the eEDM

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

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

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

(When $\theta_d = 0$)

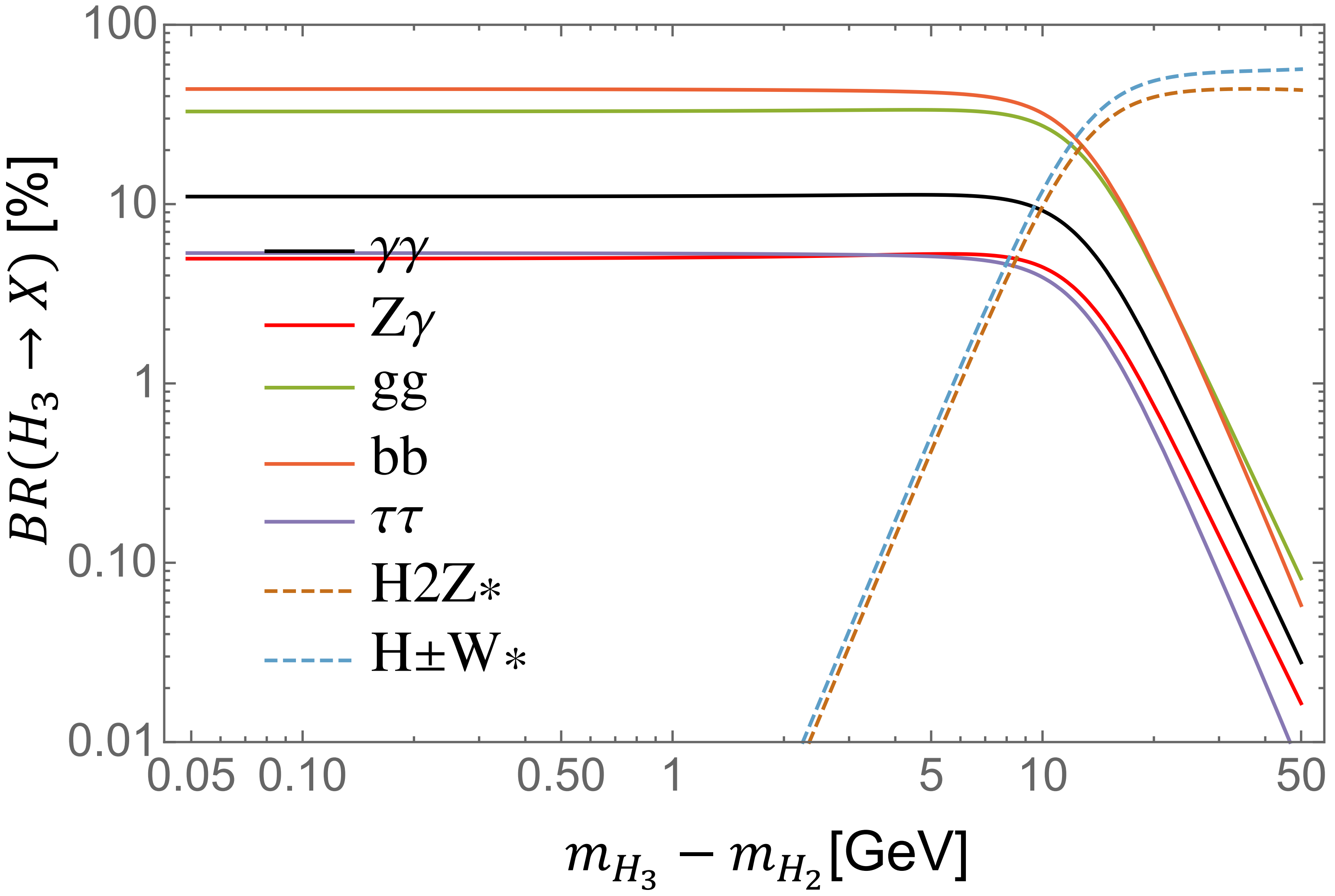


[S. Kanemura, et al., 2020]

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

$m_{H_2} = 280, m_{H^\pm} = 230,$
$|\lambda_7| = 0.3, |\zeta_u| = 10^{-2},$
$|\zeta_d| = 0.1, |\zeta_d| = 0.5$

$BR(H_3 \to X)$



100
10
1
0.10
0.01
$BR(H_3 \to X)$ [%]
$\gamma\gamma$
$Z\gamma$
gg
bb
$\tau\tau$
H2Z*
H±W*
0.05
0.10
0.50
1
5
10
50
$m_{H_3} - m_{H_2}$[GeV]