New charged scalar contributions to h → $Z\gamma$ in the 3HDM

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Plan of Talk

- Review of the 3-Higgs Doublet Models (3HDMs)

  -Motivation to study 3HDM
- Constraints on the model parameters from the measurement of $h \longrightarrow \gamma\gamma$ at the LHC
- Enhancement in $h \longrightarrow Z\gamma$ decay in the 3HDM is the main result of this talk
- Conclusion and Outlook

Review of the 3HDM

Motivation to study 3HDM

- In 3HDMs there are four charged Higgs bosons (denoted by $H_1^\pm$ and $H_2^\pm$), three CP even Higgs bosons (denoted by h, H_1 and H_2), two CP odd Higgs bosons (denoted by A_1 and A_2) and more parameters determine the phenomenology of the Higgs sector than in 2HDMs.
- It offers rich phenomenology at the LHC

In this talk, we discuss $h \rightarrow \gamma\gamma, Z\gamma$ decays in the 3HDM. These loop induced processes are sensitive to new physics contributions $H_1^\pm$ and $H_2^\pm$.

Review of the 3HDM (Cont.)

Structure of CP-Conserving 3HDM

Scalar Sector

The most general Higgs potential invariant under the $SU(2)_L \times U(1)_Y \times Z_2 \times \tilde{Z}_2$ symmetry is expressed by

$$
\begin{aligned}
V(\Phi_1, \Phi_2, \Phi_3) = {} & \sum_{i=1}^{3} m_i^2 \Phi_i^\dagger \Phi_i - (m_{12}^2 \Phi_1^\dagger \Phi_2 + m_{13}^2 \Phi_1^\dagger \Phi_3 + m_{23}^2 \Phi_2^\dagger \Phi_3 + \text{h.c.}) \\
& + \frac{1}{2} \sum_{i=1}^{3} \lambda_i (\Phi_i^\dagger \Phi_i)^2 + \rho_1 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \rho_2 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2}[\rho_3 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] \\
& + \sigma_1 (\Phi_1^\dagger \Phi_1)(\Phi_3^\dagger \Phi_3) + \sigma_2 |\Phi_1^\dagger \Phi_3|^2 + \frac{1}{2}[\sigma_3 (\Phi_1^\dagger \Phi_3)^2 + \text{h.c.}]
\end{aligned}
$$

The general 3HDM contains three scalar $SU(2)_L$ doublet fields, denoted here as

$$
\Phi_i = \begin{bmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + i z_i) \end{bmatrix}, \quad (i = 1, \dots 3),
$$

h is the lightest CP-even scalar in the 3HDM

where the v_i's are the VEVs of the Φ_i's with the sum rule $\sum_i v_i^2 \equiv v^2 = 1/(\sqrt{2}G_F) \simeq (246$ GeV$)^2$.

- The model has nine scalar physical particles: (i) three CP-even scalars (h,$H_{1,2}$), (ii) two CP-odd scalars ($A_{1,2}$), and (iii) four charged scalars ($H^{\pm}_{1,2}$).

Eighteen physical parameters

$$
m_h,\ m_{H_1},\ m_{H_2},\ m_{H_1^\pm},\ m_{H_2^\pm},\ m_{A_1},\ m_{A_2},\ v,\ \tan\beta,\ \tan\gamma,\ \theta_1,\ \theta_2,\ \alpha_{1,2},\ \theta, m_{12},\ m_{23},\ \text{and } m_{13}
$$

The VEVs may be introduced by the two ratios: $\tan\beta \equiv \frac{v_2}{v_{13}}, \quad \tan\gamma \equiv \frac{v_3}{v_1}, \quad \text{with} \quad v_{13} \equiv \sqrt{v_1^2 + v_3^2}.$

$$
m_{H^+_{1,2}}, m_h, \tan\beta, \tan\gamma, \theta_2, \alpha_{1,2}, \theta, m_{12}, m_{13}, m_{23}, v
$$

Relevant parameters to loop induced decays

Review of the 3HDM (Cont.)

Yukawa Sector

- The Yukawa Lagrangian of the 3HDM is given by

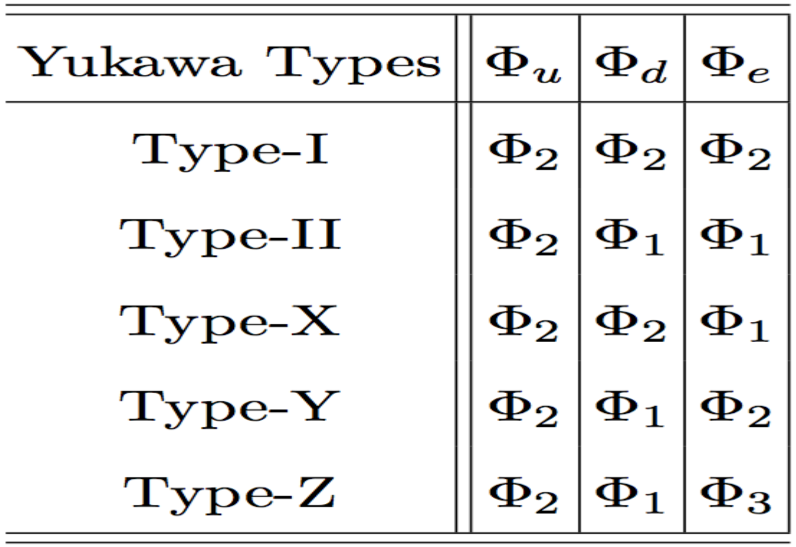
$$-\mathcal{L}_Y = Y_u \bar{Q}_L (i\sigma_2)\Phi_u^* u_R + Y_d \bar{Q}_L \Phi_d d_R + Y_e \bar{L}_L \Phi_e e_R + \text{h.c.},$$

A. G. Akeroyd, S. Moretti, K. Yagyu and E. Yildirim, Int. J. Mod. Phys. A 32, no.23n24, 1750145 (2017) [arXiv:1605.05881 [hep-ph]].

where $\Phi_{u,d,e}$ are either Φ_1, Φ_2 or Φ_3.

- Five independent types of 3HDMs exist under Z_2 symmetries

Each fermion couple to only single doublet to avoid Flavor Changing Neutral Currents (FCNCs).



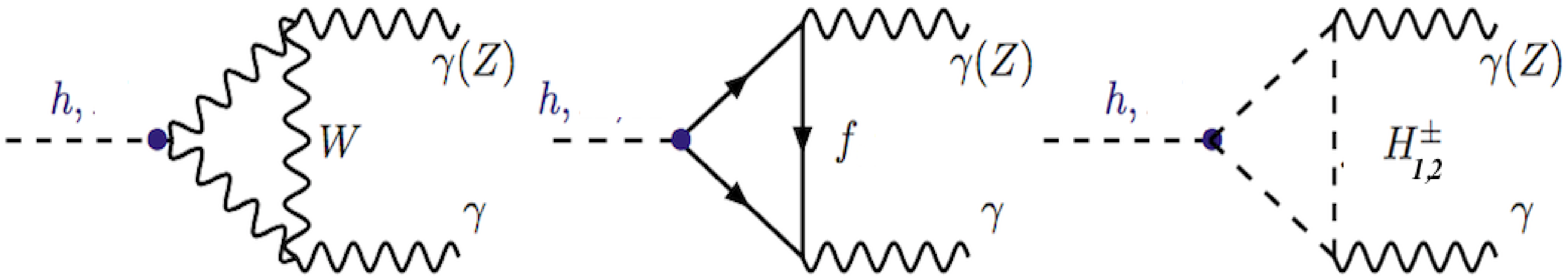
Yukawa Types	Φ_u	Φ_d	Φ_e
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Type-X	Φ_2	Φ_2	Φ_1
Type-Y	Φ_2	Φ_1	Φ_2
Type-Z	Φ_2	Φ_1	Φ_3

- ## Kinetic Lagrangian

$$\mathcal{L}_{kin} = \sum_{i=1}^{3} |D_\mu \Phi_i|^2 \ni \frac{g^2}{2} W_\mu^+ W^{\mu-} \left(\sum_{i=1}^{3} \nu_i h_i \right)$$

$$= \frac{g^2 \nu}{2} W_\mu^+ W^{-\mu} \left(\frac{1}{\nu} \sum_{i=1}^{3} \nu_i h_i \right)$$

LOOP INDUCED DECAYS INTO γγ, Zγ



The hZγ and hγγ vertices are induced at the 1-loop level.

Decay rates:

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \,|\sum_f N_c Q_f^2 g_{hff} A_{1/2}(\tau_f) + g_{hWW} A_1(\tau_W)$$

$$+ \frac{m_W^2 \lambda_{hH_i^+ H_i^-}}{2c_w^2 m_{H_i^\pm}} A_0(\tau_{H_i^\pm})\,|^2,$$

$$\Gamma(h \to Z\gamma) = \frac{G_F^2 m_W^2 \alpha m_h^3}{64\pi^4} \left(1 - \frac{m_Z^2}{m_h^2}\right) |\sum_f g_{hff} \frac{N_c Q_f \hat{v}_f}{c_w} A_{1/2}(\tau_f, \lambda_f)$$

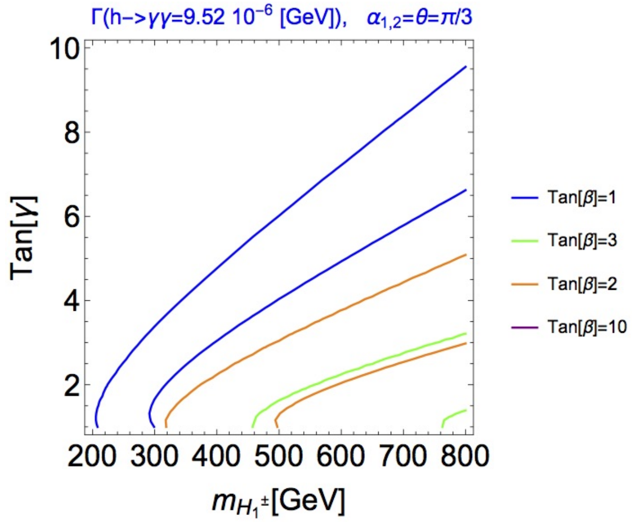
$$g_{hWW} A_1(\tau_W, \lambda_W) + \frac{m_W^2 v_{H_i^\pm}}{2c_w^2 m_{H_i^\pm}} \lambda_{hH_i^+ H_i^-} A_0(\tau_{H_i^\pm})$$

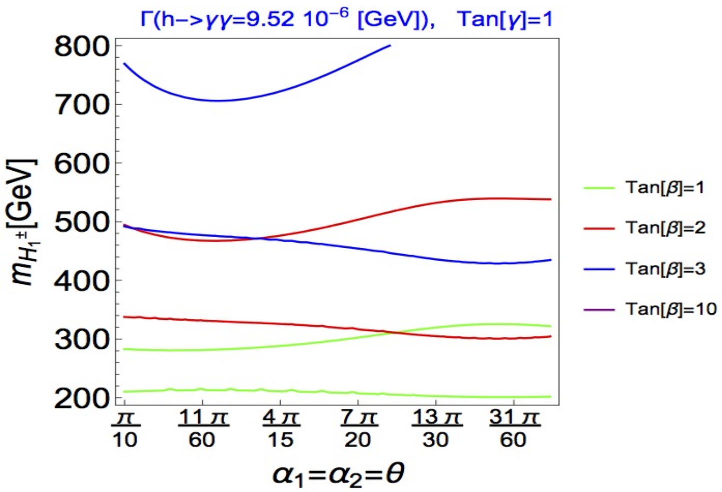
A. Djouadi, Phys. Rept. 457, 1-216 (2008) [arXiv:hep-ph/0503172 [hep-ph]].

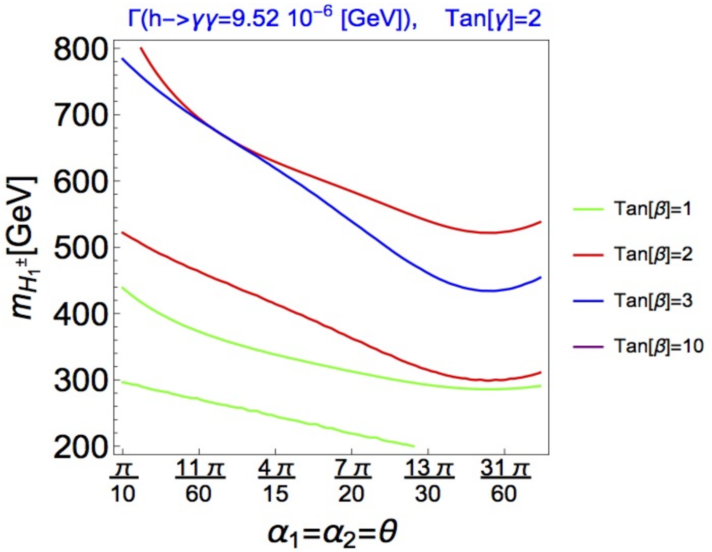
hW^+W^- coupling from kinetic Lagrangian
hff coupling from Yukawa Lagrangian
$hH_1^+H_1^-$ and $hH_2^+H_2^-$ coupling from the Higgs potential

Constraints from the LHC measurement of h → γγ on the model parameters

- We investigate the allowed parameter space of the model parameters by applying the measured values of Higgs to diphotons at the LHC.





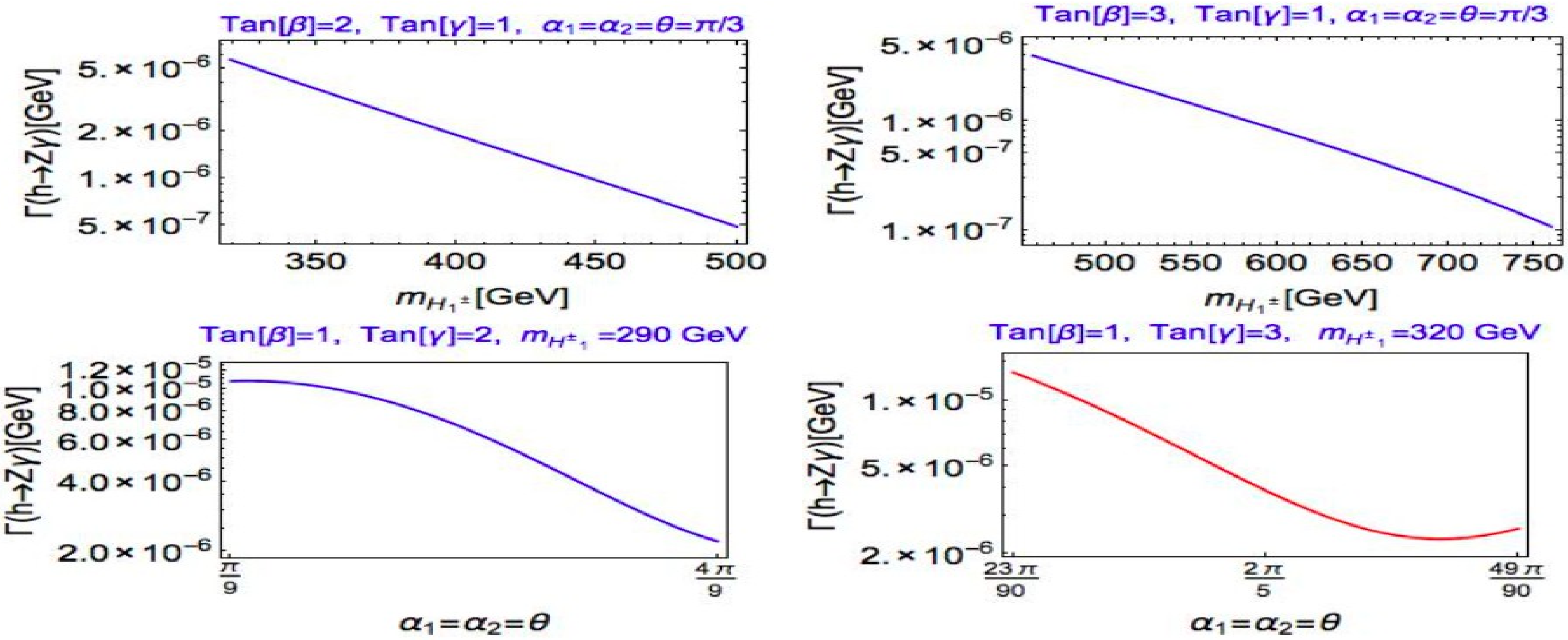


$$m_{H_2^+} = m_{H_1^+} + 100\,\mathrm{GeV}$$

- The contour lines in the figures show the allowed points of parameter spaces.
- One can see that allowed regions depend heavily upon the choice of tanβ , tanγ , and m_{H1}± , m_{H2}± and $\alpha_{1,2,}\theta$.

The dependence of Γ(h → Zγ) on the model parameters

- We will discuss the decay partial width of Γ(h → Zγ) while respecting the parameter spaces that are allowed by the Γ(h → γγ) analysis.

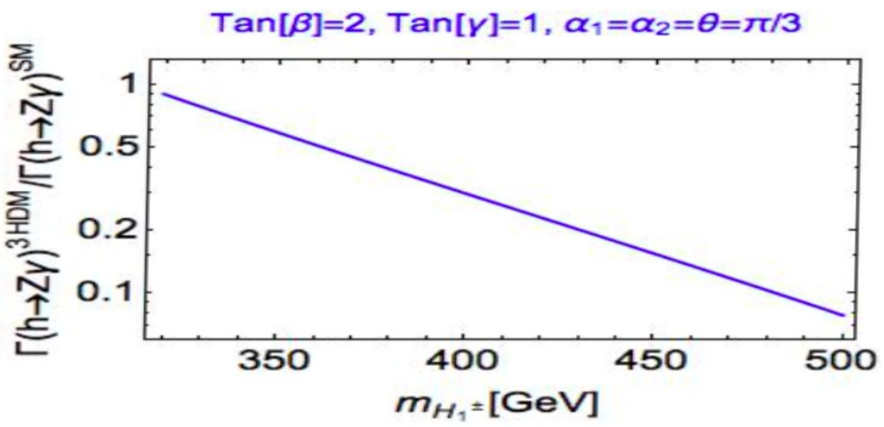


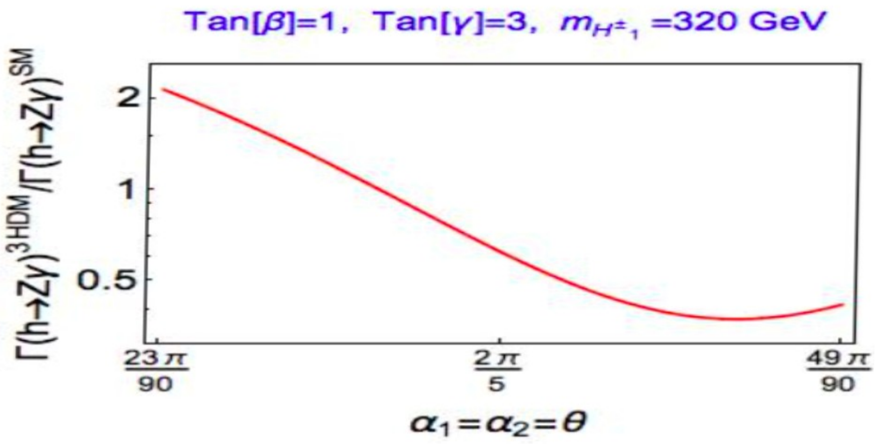
$$m_{H_2^+} = m_{H_1^+} + 100\,\mathrm{GeV}$$

Γ(h → Zγ) is sensitive to tan(β), tan(γ), CP even mixing angles ($\alpha_{1,2}$, θ) and $m_{H_{1,2}}$±

Enhancement of h → Zγ from new charged scalars

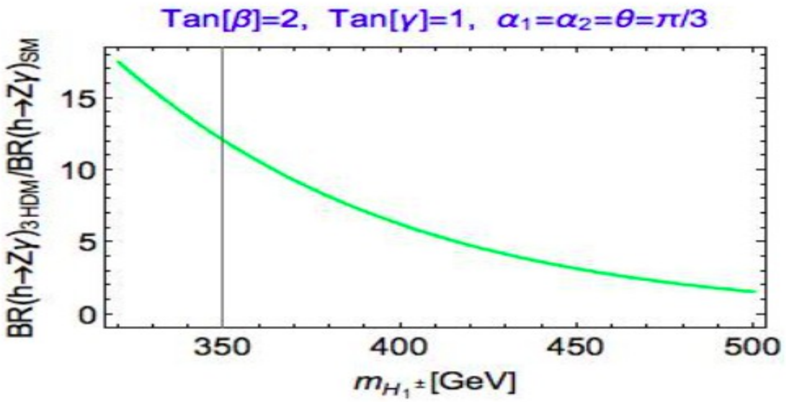
We indicate the deviation in the decay partial width of Γ(h → Zγ) with respect to the SM prediction.

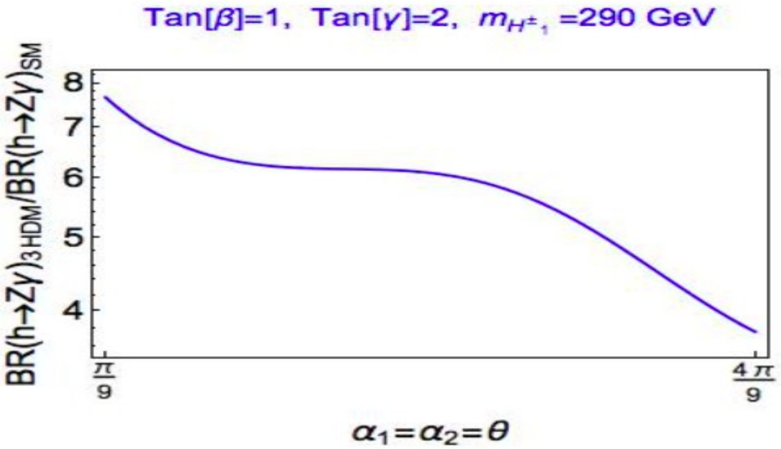




The deviation in Γ(h → Zγ) relative to the SM prediction increases with large values of $\alpha_{1,2} = \theta$ and $m_{H1,2}$± .

- We present the deviation in the branching ratio of BR(h → Zγ) with respect to the SM value.





Enhancement in BR(h → Zγ) occur in some parameter regions

- WHY the deviation in the BR(h → Zγ) relative to the SM prediction is larger than that in Γ(h → Zγ) relative to the SM prediction?
- The partial widths of (h → ff, gg) in Type-I 3HDM are significantly reduced with respect to their SM value so the total decay width in Type-I 3HDM is smaller than that in the SM.

Conclusion and Outlook

We have seen that

- ✓ the new charged Higgs bosons $H_{1,2}^{\pm}$ can significantly alter the decay widths $h \rightarrow Z\gamma$
- ✓ model parameters affect significantly to this decay
- ✓ $\mathrm{BR}(h \rightarrow Z\gamma)_{\mathrm{3HDM}}$ enhances considerably compared to the SM prediction, while respecting constraints from $h \rightarrow \gamma\gamma$
- ✓ the Type-I and Type-Z 3HDM are not disentangled via $Z\gamma$ decay since $Z\gamma$ decay is dominated by the $H_1^{\pm}$ and $H_2^{\pm}$ bosons loop contributions
- ✓ The current searches at the LHC have a limit of about 4 times the $h \rightarrow Z\gamma$ signal strength in the Standard Model. Hence one would expect this decay to be observed in the high-luminosity run of the LHC if its branching ratio is close to that of the prediction in the Standard Model.

Thank You!