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Decays of Standard Model–Like Higgs Boson $h \to \gamma\gamma$, $Z\gamma$ in a Minimal Left-Right Symmetric Model

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Two decay channels $h \to \gamma\gamma$, $Z\gamma$ of the Standard Model–like Higgs in a left-right symmetry model are investigated using recent experimental data. We show that there exist one-loop contributions that affect the $h \to Z\gamma$ amplitude, but not the $h \to \gamma\gamma$ amplitude. From numerical investigations, we show that the signal strength $\mu_{Z\gamma}$ of the decay $h \to Z\gamma$ is still constrained strictly by that of $h \to \gamma\gamma$, namely $|\Delta\mu_{\gamma\gamma}| < 38\%$ results in maximum $|\Delta\mu_{Z\gamma}| < 46\%$. On the other hand, the future experimental sensitivity $|\Delta\mu_{\gamma\gamma}| = 4\%$ still allows $|\Delta\mu_{Z\gamma}|$ to reach values larger than the expected sensitivity of $|\Delta\mu_{Z\gamma}| = 23\%$.

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1. Introduction

The Standard Model–like (SM-like) Higgs decay $h \to Z\gamma$ is one of the most important channels being researched experimentally [1]. Meanwhile, the experimental evidence of this loop-induced decay relating to the effective coupling $hZ\gamma$ has been reported by ATLAS and CMS recently [2,3], in agreement with the SM prediction within 1.9 standard deviations. Experimental data show that the effective coupling $h\gamma\gamma$ derived from $h \to \gamma\gamma$ decay rates is constrained very strictly [4]. In contrast, the effective coupling $hZ\gamma$ in many models beyond the SM (BSM) might differ considerably from the SM prediction, because the Z couplings to new particles are less strict than those of the photon. Hence, studying the effective $hZ\gamma$ couplings will be an indirect channel to determine the properties of new particles. Controlled by the strict experimental constraint of the decay $h \to \gamma\gamma$, constraints of the SM-like Higgs decay $h \to Z\gamma$ affected by new fermions and charged scalars were studied in several BSMs such as 3-3-1 models [5,6], only Higgs extended SM versions [7–10], $U(1)$ gauge extensions from the SM [11,12], supersymmetric models [13–15], chiral extension of the SM [16], etc. Previous studies of $h \to Z\gamma$ in left-right symmetric models ignored one-loop contributions relating to the diagrams consisting

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Table 1. Baryon and lepton numbers of fermions in the MLRSM.

f	$e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$	u, c, t, s
L	1	0
B	0	$\frac{1}{3}$

of both virtual Higgs and gauge particles in the loops [17,18], where the h-Higgs–gauge boson couplings were assumed to be suppressed.

The experimental results have been updated for the loop-induced Higgs decays $h \to \gamma\gamma$ [19–21] and $h \to Z\gamma$ [22]. In the future of this project, the significant strength of the decay $h \to Z\gamma$, denoted as $\mu_{Z\gamma}$, can reach $\Delta\mu_{Z\gamma} \equiv \mu_{Z\gamma} - 1 = \pm 0.23$, whereas that of the channel $h \to \gamma\gamma$ can reach around $\Delta\mu_{\gamma\gamma} \equiv \mu_{\gamma\gamma} - 1 = \pm 0.04$, as determined from two CMS and ATLAS experiments [23]. In addition, the ATLAS expected significance at the High-Luminosity Large Hadron Collider (HL-LHC) for the $h \to Z\gamma$ channel will be 4.9σ with 3000 fb^{-1}. Also, the Circular Electron Positron Collider (CEPC) [24] can reach a sensitivity of $\mu_{Z\gamma} = 1 \pm 0.22$ [25].

One interesting extension of the BSM models is an extension of the lepton sector. Namely, the minimal left-right symmetry model (MLRSM) is constructed based on the parity symmetry $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ [26–28], which contains Higgs fields included in two $SU(2)_L$ triplets denoted as $\Delta_{L,R}$ and a bi-doublet field Φ playing the SM Higgs role. Therefore, the MLRSM allows us to solve the parity problem of the SM as well as the neutrino oscillation data through the seesaw mechanism. Besides, it contains extended particles which may result in interesting consequences for rare decays such as Higgs boson decay $h \to Z\gamma$.

This work is organized as follows. In Sect. 2, we present an overview of the MLRSM, including the particle content and physical states. In Sect. 3, we present the necessary couplings that generate one-loop contributions to the decays $h \to \gamma\gamma, Z\gamma$. We will also collect analytic formulas to determine the decay rates, recapitulating some new contributions that were not discussed previously. Numerical results will be investigated in Sect. 4. Namely, we will investigate the dependence of $\mu^{\text{MLRSM}}_{Z\gamma}$ on several important parameters in this model. Finally, a summary is given in Sect. 5.

2. The MLRSM

2.1. *Review of the model*

All needed ingredients relevant to one-loop contributions to the decay amplitudes $h \to Z\gamma, \gamma\gamma$ will be collected in this section. Most generally, the electric charge operator can be written as [29,30]:

$$Q = T_3^R + T_3^L + \frac{B-L}{2} = T_3^{L,R} + \frac{Y}{2}, \tag{1}$$

where $T_i^{L,R}$ are the generators of the gauge groups $SU(2)_{L,R}$; B (L) is the baryon (lepton) number defining the $U(1)_{B-L}$ group in the MLRSM. The baryon and lepton numbers of the fermions can be written as in Table 1.

With this information, we can write down the lepton and fermion representations as follows:

$$L'_{Li} = \begin{pmatrix} \nu'_{Li} \\ l'_{Li} \end{pmatrix} \sim (2, 1, -1),\ L'_{Ri} = \begin{pmatrix} \nu'_{Ri} \\ l'_{Ri} \end{pmatrix} \sim (1, 2, -1), \tag{2}$$

$$Q'_{Li} = \begin{pmatrix} u'_{Li} \\ d'_{Li} \end{pmatrix} \sim \left(2, 1, \frac{1}{3}\right),\ Q'_{Ri} = \begin{pmatrix} u'_{Ri} \\ d'_{Ri} \end{pmatrix} \sim \left(1, 2, \frac{1}{3}\right), \tag{3}$$

where $i = 1, 2, 3$ is the flavor index.

Gauge boson and fermion masses are originated from the following scalar sector, consisting of a bi-doublet and two triplet scalar fields $\Delta_{L,\,R}$ satisfying

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix},\ \widetilde{\Phi} = \sigma_2 \Phi^* \sigma_2 \sim (2, 2, 0),\ \Delta_{L,R} = \begin{pmatrix} \frac{\delta^+_{L,R}}{\sqrt{2}} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\frac{\delta^+_{L,R}}{\sqrt{2}} \end{pmatrix} \sim (3, 1, 2). \tag{4}$$

The Higgs components develop vacuum expectation values (VEVs) defined as

$$\langle\Phi\rangle = \begin{pmatrix} \langle\phi_1^0\rangle & 0 \\ 0 & \langle\phi_2^0\rangle \end{pmatrix};\ \langle\Delta_{L,R}\rangle = \begin{pmatrix} 0 & 0 \\ \langle\delta^0_{L,R}\rangle & 0 \end{pmatrix}, \tag{5}$$

where the neutral Higgs components are expanded as follows:

$$\phi_i^0 = \langle\phi_i^0\rangle + \frac{r_i + ia_i}{\sqrt{2}}, \langle\phi_1^0\rangle = \frac{k_1}{\sqrt{2}},\ \langle\phi_2^0\rangle = \frac{k_2 e^{i\alpha}}{\sqrt{2}},\ i = 1, 2;$$

$$\delta^0_{L,R} = \langle\delta^0_{L,R}\rangle + \frac{v_{L,R}e^{i\theta_{L,R}} + r_{L,R} + ia_{L,R}}{\sqrt{2}},\ \langle\delta^0_L\rangle = \frac{v_L e^{i\theta_L}}{\sqrt{2}},\ \langle\delta^0_R\rangle = \frac{v_R}{\sqrt{2}}. \tag{6}$$

The symmetry-breaking pattern in MLRSM happens in the two following steps: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \xrightarrow{v_R \neq 0, k_1, k_2, v_L = 0} SU(2)_L \otimes U(1)_Y \xrightarrow{k_1, k_2, v_L \neq 0} U(1)_Q$, which corresponds to the reasonable limits that $v_R \gg k_1, k_2 \gg v_L$. Only new gauge bosons will be massive after the first step. The second step is the SM symmetry-breaking generating masses for the SM particles. When the symmetry is broken in step two, only $U(1)_Q$ remains unbroken, where Q is the quantifier. As a result, the photon A_μ has no mass. We stress that the MLRSM contains no more than three scalar multiplets (ϕ, $\Delta_{L,\,R}$). The physical spectrum and masses of all particles in the model under consideration are summarized as follows.

2.2. *Fermions*

Physical fermion states and their masses always relate to the Yukawa interactions, which are included in the following Lagrangian parts for leptons and quarks:

$$\mathcal{L}^Y_\ell = -\overline{L'_{Li}}\left(f^e_{ij}\Phi + \widetilde{f}^e_{ij}\widetilde{\Phi}\right)L'_{Rj} - \sum_{X=L,R} Y^e_{X,ij}\overline{L'^c_{Xi}}i\sigma_2\Delta_X L'_{Xj} + \text{h.c.},$$

$$\mathcal{L}^Y_q = -\overline{Q'_{Li}}\left(f^q_{ij}\Phi + \widetilde{f}^q_{ij}\widetilde{\Phi}\right)Q'_{Rj} + \text{h.c.} \tag{7}$$

Then, the mass terms for leptons and quarks are computed. We will use the results for fermion masses and mixing presented in Refs. [29,30], i.e. all the original and the physical states of fermions are the same. They are identified with the SM ones and will be denoted as $e_{aL,\,R}$, $u_{aL,\,R}$, and $d_{aL,\,R}$ in this work. The mass matrices M_ℓ and $M_{u,\,d}$ for charged leptons and up and down quarks are

$$M_\ell = \frac{k_1 f^e + k_2 \tilde{f}^e}{\sqrt{2}} = \frac{k\left(c_\beta f^e + s_\beta \tilde{f}^e\right)}{\sqrt{2}},$$

$$M_u = \frac{k_1 f^q + k_2 \tilde{f}^q}{\sqrt{2}} = \frac{k\left(s_\beta f^q + c_\beta \tilde{f}^q\right)}{\sqrt{2}},$$

$$M_d = \frac{k_1 f^q + k_2 \tilde{f}^q}{\sqrt{2}} = \frac{k\left(c_\beta f^q + s_\beta \tilde{f}^q\right)}{\sqrt{2}}, \quad (8)$$

where

$$k^2 \equiv k_1^2 + k_2^2,\ t_\beta \equiv \frac{s_\beta}{c_\beta} = \frac{k_1}{k_2}. \quad (9)$$

As we will show below, the matching condition to the SM leads to $k = 246$ GeV and the Yukawa couplings of quarks defined in the SM can be seen as follows: $c_\beta f^e + s_\beta \tilde{f}^e \to y^e$, $s_\beta f^q + c_\beta \tilde{f}^q \to y^u$, and $k_1 f^q + k_2 \tilde{f}^q \to y^d$. Here, we fix $\alpha = 0$ so that the value of $t_\beta = s_\beta / c_\beta$ can be small, namely $t_\beta \geq 1.2$ [31]. The three above fermion mass matrices are denoted as M_f with $f = \ell, u, d$ and can be diagonalized by two unitary transformations V_f^L and V_f^R as follows: $V_f^{L\dagger} M_f V_f^R = \hat{M}_f = \mathrm{diag}\left(m_{f,1},\ m_{f,2},\ m_{f,3}\right)$. Here $m_{f,\,i}$ with $i = 1, 2, 3$ and $f = \ell, u, d$ denotes the physical masses of charged leptons and of up and down quarks. The transformation between the flavor basis $f'_{L(R)} = (f'_1,\ f'_2,\ f'_3)^T_{L(R)}$ and the mass basis $f_{L(R)} = (f_1,\ f_2,\ f_3)^T_{L(R)}$ is $f'_{L(R)} = V_f^{L(R)} f_{L(R)}$. As we will show below, the couplings of the SM-like Higgs boson with charged leptons and quarks are the same as the SM results.

2.3. *Gauge bosons*

The covariant derivative corresponding to the symmetry of the MLRSM is defined as [29]:

$$D_\mu = \partial_\mu - i g_L \sum_{i=1}^{3} T_L^a W_{L\nu}^a + i g_R \sum_{i=1}^{3} T_R^a W_{R\nu}^a - i g' \frac{B-L}{2} B_\mu, \quad (10)$$

where $g_{L,\,R}$ and g' are the $SU(2)_{L,\,R}$ and $U(1)_{B-L}$ gauge couplings, respectively.

The Lagrangian for scalar kinetic parts is written as

$$\mathcal{L}_s = \sum_{S=\Phi,\Delta_{L,R}} \mathcal{L}_S = \sum_{S=\Phi,\Delta_{L,R}} \mathrm{Tr}\left[\left(D_\mu S\right)^\dagger \left(D^\mu S\right)\right]. \quad (11)$$

The particular forms of covariant derivatives for the scalar multiplets are

$$D_\mu \Phi = \partial_\mu \Phi - i g_L \frac{\sigma^b}{2} W_{L\nu}^b \Phi + i g_R \Phi \frac{\sigma^a}{2} W_R^a,$$

$$D_\mu \Delta_X = \partial_\mu \Delta_X - i \frac{g_X}{2} \left(\sigma^a \Delta_X - \Delta_X \sigma^a\right) W_X^a - i g' I_2 B_\mu \Delta_X, \quad (12)$$

where $X = L, R$, σ^a is the Pauli matrix corresponding to the $SU(2)$ doublet representation of $T_{L,R}^a$ with $a = 1, 2, 3$. Therefore, the mass terms of gauge bosons are derived from the VEVs of

Higgs components as follows:

$$\begin{aligned}\langle\mathcal{L}_s\rangle &= \sum_{S=\Phi,\Delta_{L,R}}\langle\mathcal{L}_S\rangle \\ &= \frac{1}{8}\left(k^2+4v_L^2\right)g_L^2 W_L^{3\mu}W_{L\mu}^3 - \frac{1}{4}g_L g_R k^2 W_L^{3\mu}W_{R\mu}^3 \\ &+ \frac{1}{8}\left(k^2+4v_R^2\right)g_R^2 W_R^{3\mu}W_{R\mu}^3 - g_L g' W_L^{3\mu}B^\mu - g_R g' v_R^2 W_R^{3\mu}B_\mu \\ &+ \frac{1}{2}g'^2(v_L^2+v_R^2)B^\mu B_\mu + \frac{1}{4}g_L^2\left(k^2+2v_L^2\right)W_L^{+\mu}W_{L\mu}^- - \frac{1}{2}g_L g_R k_1 k_2 e^{i\alpha}W_L^{+\mu}W_{R\mu}^- \\ &- \frac{1}{2}g_L g_R k_1 k_2 e^{-i\alpha}W_L^{+\mu}W_{R\mu}^- + \frac{1}{4}g_R^2\left(k^2+2v_R^2\right)W_R^{+\mu}W_{R\mu}^-,\end{aligned} \tag{13}$$

where k is defined as in Eq. (9). The mass terms of the neutral and charged gauge bosons read:

$$\begin{aligned}\mathcal{L}_g^{\mathrm{mass}} &= \frac{1}{2}\left(W_L^{3\mu}W_R^{3\mu}B^\mu\right)\begin{pmatrix}\frac{1}{4}\left(k_1^2+k_2^2+4v_L^2\right)g_L^2 & -\frac{1}{4}g_L g_R(k_1^2+k_2^2) & -g_R g' v_L^2 \\ -\frac{1}{4}g_L g_R(k_1^2+k_2^2) & \frac{1}{4}\left(k_1^2+k_2^2+4v_R^2\right)g_R^2 & -g_R g' v_R^2 \\ -g_R g' v_L^2 & -g_R g' v_R^2 & g'^2(v_L^2+v_R^2)\end{pmatrix} \\ &\times\begin{pmatrix}W_{L\mu}^3 \\ W_{R\mu}^3 \\ B_\mu\end{pmatrix} + \left(W_L^{+\mu}W_R^{+\mu}\right)\begin{pmatrix}\frac{1}{4}\left(k_1^2+k_2^2+2v_L^2\right)g_L^2 & -\frac{1}{2}g_L g_R k_1 k_2 e^{i\alpha} \\ -\frac{1}{2}g_L g_R k_1 k_2 e^{-i\alpha} & \frac{1}{4}\left(k_1^2+k_2^2+2v_R^2\right)g_R^2\end{pmatrix}\begin{pmatrix}W_{L\mu}^- \\ W_{R\mu}^-\end{pmatrix},\end{aligned} \tag{14}$$

where $W_{X\mu}^\pm \equiv \frac{1}{\sqrt{2}}\left(W_{X\mu}^1 \mp iW_{X\mu}^2\right)$ with $X = L, R$. The mixing angle ξ between two singly charged gauge bosons $W_L^\pm$ and $W_R^\pm$ is determined by the following formula:

$$\tan 2\xi = \frac{-4g_L g_R k_1 k_2}{\left(g_R^2-g_L^2\right)\left(k_1^2+k_2^2\right)+2\left(g_R^2 v_R^2 - g_L^2 v_L^2\right)}. \tag{15}$$

Using the approximation that $\tan 2\xi \ll 1 \Rightarrow \tan 2\xi \approx \sin 2\xi \approx 2\sin\xi \approx 2\xi$, and $v_L \ll k_1, k_2 \ll v_R$, the $W_L - W_R$ mixing angle ξ is

$$2\xi = \frac{-2g_L k_1 k_2}{g_R v_R^2},\ \frac{k^2}{v_R^2} \approx x \ll 1,\ \frac{v_L^2}{v_R^2} \approx 0,\ \frac{v_L^2}{k^2} \approx x_L \ll 1. \tag{16}$$

The singly charged gauge bosons $W_{L,R}^\pm$ can be written as functions of the mass basis $(W_1^\pm, W_2^\pm)$ as follows:

$$\begin{pmatrix}W_L^\pm \\ W_R^\pm\end{pmatrix} = \begin{pmatrix}c_\xi & -s_\xi e^{i\alpha} \\ s_\xi e^{-i\alpha} & c_\xi\end{pmatrix}\begin{pmatrix}W_1^\pm \\ W_2^\pm\end{pmatrix}, \tag{17}$$

where $c_\xi \equiv \cos\xi$ and $s_\xi \equiv \sin\xi$. The respective charged gauge boson masses are found to be

$$m_{W_1}^2 \approx \frac{1}{4}k^2 g_L^2, \quad m_{W_2}^2 \approx \frac{1}{2}g_R^2 v_R^2. \tag{18}$$

Identifying that $W_1^\pm \equiv W^\pm$ in the SM, we get $k_1^2 + k_2^2 = k^2 \equiv v^2 = (246\ \mathrm{GeV})^2$.

The original neutral gauge basis ($W^3_{L\mu}$, $W^3_{R\mu}$, B_μ) is expressed in terms of the mass basis (A_μ, $Z_{1\mu}$, $Z_{2\mu}$) as follows:

$$\begin{pmatrix} W^3_{L\mu} \\ W^3_{R\mu} \\ B_\mu \end{pmatrix} = C^T \begin{pmatrix} A_\mu \\ Z_{1\mu} \\ Z_{2\mu} \end{pmatrix}, \tag{19}$$

where

$$C = \begin{pmatrix} s_{z_2} & c_R c_{z_2} & c_{z_2} s_R \\ c_{z_2} c_{z_3} & -c_R c_{z_3} s_{z_2} - s_R s_{z_3} & -c_{z_3} s_R s_{z_2} + c_R s_{z_3} \\ -c_{z_2} s_{z_3} & -c_{z_3} s_R + c_R s_{z_2} s_{z_3} & c_R c_{z_3} + s_R s_{z_2} s_{z_3} \end{pmatrix} \tag{20}$$

and the mixing angles t_R, t_{z_2}, t_{z_3} are given by

$$t_R = \frac{g_R}{g'}, \quad t_{z_2} = \frac{g_R g'}{g_L\sqrt{g'^2 + g_R^2}}, \quad t_{2z_3} = \frac{-g_R^2 k^2 \sqrt{g_L^2 g'^2 + g_L^2 g_R^2 + g'^2 g_R^2}}{2v_R^2\left(g_R^2 + g'^2\right)}. \tag{21}$$

State synchronization with the SM is as follows: $W^3_{L\mu} \equiv W^3_\mu$, $Z_{1\mu} \equiv Z_\mu$ in the limits $c_{z_3} \to 1$, then we also have

$$s_{z_2} \equiv s_W,\ c_{z_2} \equiv c_W \Rightarrow t_W = t_{z_2} = s_R t'. \tag{22}$$

The Weinberg angle θ_W is identified from the definition $\cos\theta_W \equiv c_W \equiv \frac{m_{W_1}}{m_{Z_1}} \approx c_{z_2}$. Then, the neutral gauge boson masses of Z_1, Z_2, and the photon A are given by

$$m^2_{Z_1} \approx \frac{g_L^2 v^2}{4c_W^2},\ m^2_{Z_2} \approx \frac{g_R^2 v_R^2}{1 - \left(g_L^2/g_R^2\right) t_W^2}, \text{ and } m_A^2 = 0. \tag{23}$$

In addition, $Z_1 \equiv Z$ and $Z_2 \equiv Z'$ are, respectively, the SM gauge boson Z found experimentally, and the heavy one appearing in the MLRSM.

2.4. *Higgs bosons*

The MLRSM scalar potential is written as [29]:

$$\begin{aligned}
V_h = &-\mu_\Phi^2 \mathrm{Tr}\left[\Phi^\dagger\Phi\right] - \mu_\Phi'^2\left(\mathrm{Tr}\left[\Phi^\dagger\widetilde{\Phi}\right] + \mathrm{Tr}\left[\widetilde{\Phi}^\dagger\Phi\right]\right) - \mu_\Delta^2 \sum_{X=L,R} \mathrm{Tr}\left[\Delta_X^\dagger\Delta_X\right] \\
&+ \lambda_1\left(\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right)^2 + \lambda_2\Big(\left(\mathrm{Tr}\left[\Phi^\dagger\widetilde{\Phi}\right]\right)^2 + \left(\mathrm{Tr}\left[\widetilde{\Phi}^\dagger\Phi\right]\right)^2\Big) + \lambda_3\left(\mathrm{Tr}\left[\Phi^\dagger\widetilde{\Phi}\right]\mathrm{Tr}\left[\widetilde{\Phi}^\dagger\Phi\right]\right) \\
&+ \lambda_4 \mathrm{Tr}\left[\Phi^\dagger\Phi\right]\left(\mathrm{Tr}\left[\Phi^\dagger\widetilde{\Phi}\right] + \mathrm{Tr}\left[\widetilde{\Phi}^\dagger\Phi\right]\right) + \rho_1\left(\mathrm{Tr}\left[\Delta_L^\dagger\Delta_L\right]^2 + \mathrm{Tr}\left[\Delta_R^\dagger\Delta_R\right]^2\right) \\
&+ \rho_2 \sum_{X=L,R}\left(\mathrm{Tr}\left[\Delta_X^\dagger\Delta_X^\dagger\right]\mathrm{Tr}\left[\Delta_X\Delta_X\right]\right) + \rho_3\left(\mathrm{Tr}\left[\Delta_L^\dagger\Delta_L\right]\mathrm{Tr}\left[\Delta_R^\dagger\Delta_R\right]\right) \\
&+ \sum_{X\neq Y=L,R}\rho_4\left(\mathrm{Tr}\left[\Delta_X^\dagger\Delta_X^\dagger\right]\mathrm{Tr}\left[\Delta_Y\Delta_Y\right]\right) + \alpha_1 \mathrm{Tr}\left[\Phi^\dagger\Phi\right]\sum_{X=L,R}\left(\mathrm{Tr}\left[\Delta_X^\dagger\Delta_X\right]\right) \\
&+ \left\{\alpha_2 e^{i\delta_2}\sum_{X=L,R}\left(\mathrm{Tr}\left[\Phi^\dagger\widetilde{\Phi}\right]\mathrm{Tr}\left[\Delta_X^\dagger\Delta_X\right]\right) + \mathrm{h.c.}\right\} + \sum_{X=L,R}\left(\alpha_3 \mathrm{Tr}\left[\Phi\Phi^\dagger\Delta_X\Delta_X^\dagger\right]\right) \\
&+ \left\{\alpha_4 \mathrm{Tr}\left[\Phi^\dagger\Delta_L^\dagger\Phi\Delta_R\right] + \alpha_5 \mathrm{Tr}\left[\Phi^\dagger\Delta_L^\dagger\widetilde{\Phi}\Delta_R\right] + \alpha_6 \mathrm{Tr}\left[\widetilde{\Phi}^\dagger\Delta_L^\dagger\Phi\Delta_R\right] + \mathrm{h.c.}\right\}.
\end{aligned} \tag{24}$$

From the minimal conditions of the Higgs potential given in Eq. (24), three parameters μ_Φ^2, $\mu_\Phi'^2$, and μ_Δ^2 are expressed as functions of other independent parameters. Inserting them into the Higgs potential (24), we can determine all Higgs boson masses and physical states. Firstly, the original and the mass base of neutral CP-even Higgs bosons are related to each other as follows:

$$\begin{pmatrix} h^0 \\ H_1^0 \end{pmatrix} = \begin{pmatrix} s_\beta & c_\beta \\ -c_\beta & s_\beta \end{pmatrix}\begin{pmatrix} r_1 \\ r_2 \end{pmatrix}. \tag{25}$$

We note that Eq. (25) does not use the the limit $k_1 \gg k_2$ mentioned in Ref. [29], which gives $t_\beta = \frac{k_1}{k_2} \approx \frac{1}{\epsilon_2} \gg 1$, $c_\beta = \frac{1}{\sqrt{t_\beta^2+1}} \approx \frac{1}{t_\beta} \approx \epsilon_2$, $s_\beta \approx 1$, and $\epsilon_1 \equiv k_1/v_R$, $\epsilon_2 \equiv k_2/k_1$. Besides that, from Eq. (25) we get the same result as in Ref. [29] in this limit. In this study, the SM-like Higgs mass is calculated approximately to the order $\epsilon^2 = v^2/v_R^2$, namely

$$\begin{aligned}
m_{h^0}^2 = &\left[2\lambda_1 + 8c_\beta^2 s_\beta^2\left(2\lambda_2+\lambda_3\right) + 8c_\beta s_\beta\lambda_4\right]v^2 - \frac{8\left(2c_\beta^2-1\right)^3 v^4}{\alpha_3 v_R^2} \\
&\times\left[4c_\beta^4(2\lambda_2+\lambda_3)^2 - 4s_\beta c_\beta\lambda_4(2\lambda_2+\lambda_3) - 4c_\beta^2(2\lambda_2+\lambda_3)^2 - \lambda_4^2\right].
\end{aligned} \tag{26}$$

The SM-like Higgs property appears in Eq. (26) as $m_{h^0}^2 \simeq v^2 \times \mathcal{O}(\frac{v^2}{v_R^2}) \sim v^2$ because $\mathcal{O}(\epsilon^2) \simeq 0$ when $v^2 \ll v_R^2$. In this limit, $h^0 \equiv h$ can be identified with the SM-like Higgs boson with mass $m_h = 125.38$ GeV confirmed experimentally [1]. Then the Higgs self-coupling λ_1 is expressed as follows:

$$\lambda_1 = \frac{1}{2}\left(\frac{m_h^2}{v^2} - 8c_\beta\left[s_\beta^2 c_\beta(2\lambda_2+\lambda_3)+\lambda_4 s_\beta\right]\right.$$
$$\left. - \frac{8v^2\left(2c_\beta^2-1\right)^3\left[2c_\beta s_\beta(2\lambda_2+\lambda_3)+\lambda_4\right]^2}{\alpha_3 v_R^2}\right). \quad (27)$$

We note that Eq. (26) for SM-like Higgs mass is consistent with Refs. [32–34], implying that the m_h value is still at the electroweak scale even in the case of large t_β. Therefore, a value of $t_\beta \geq 1.2$ is still allowed to get the SM-like Higgs mass consistent with the experiment.

Regarding the SM-like Higgs couplings with charged leptons and fermions, using Eq. (25) for the Yukawa Lagrangian in Eq. (7), we derive easily that

$$\mathcal{L}^{hff} = \sum_{f=\ell,u,d}\frac{\sqrt{2}}{k}\overline{f'_L}\hat{M}_f f'_R h + \text{H.c.} \simeq \sum_{f=\ell,u,d}\frac{g}{\sqrt{2}m_W}\overline{f_L}M_f f_R h + \text{H.c.}, \quad (28)$$

where $k = 246 = g/(\sqrt{2}m_W)$, and the transformation in Eq. (28) is based on discussion relating to Eq. (8). Therefore, the SM-like Higgs couplings with charged fermions can be identified with the SM results.

Similarly, the original and mass states of the singly charged Higgs bosons have the following relations:

$$\begin{pmatrix}\phi_1^\pm\\ \phi_2^\pm\end{pmatrix} = \begin{pmatrix}-s_\beta & c_\beta\\ c_\beta & s_\beta\end{pmatrix}\begin{pmatrix}G_W^\pm\\ H_1^\pm\end{pmatrix},$$
$$H_2^\pm \simeq \delta_L^\pm,\ G_{W_2}^\pm \simeq \delta_R^\pm, \quad (29)$$

where $G_{W_2}^\pm$ is massless, corresponding to the Goldstone boson eaten up by $W_2^\pm$, and the remaining squared masses of singly charged Higgs bosons are

$$m_{H_1^\pm}^2 = \frac{\alpha_3 v_R^2}{2\left(2s_\beta^2-1\right)},\ m_{H_2^\pm}^2 = \frac{1}{2}\left(\rho_3 - 2\rho_1\right)v_R^2. \quad (30)$$

Besides that, two components (δ_L^{++}, δ_R^{++}) are also physical states with the following masses:

$$m_{H_1^{\pm\pm}}^2 = \frac{1}{2}v_R^2(\rho_3-2\rho_1), \qquad m_{H_2^{\pm\pm}}^2 = 2v_R^2\rho_2. \quad (31)$$

3. Couplings and analytic formulas involved with loop-induced Higgs decays

3.1. *Couplings*

From the above Higgs potential and the discussion on the masses and mixing of Higgs bosons, all Higgs self-couplings of h giving one-loop contributions to the decays $h \to \gamma\gamma$, $Z\gamma$ can be derived analytically. From the general notations in the interacting Lagrangian: $-V_h \to \mathcal{L}_{hSS} = \sum_{S_i,S_j=H_{1,2}^\pm,H_{1,2}^{\pm\pm}}(-\lambda_{hS_{ij}}hS_i^{Q_S}S_j^{-Q_S} + \text{h.c.}) + \dots$, the Feynman rule $-i\lambda_{hSS}$ corresponds to the vertex hSS. All nonzero factors λ_{hSS} are given in Table 2. We note that the vertex factors in Table 2 are derived following the general notation defined in Ref. [35], so that we can use the analytic formulas to compute the partial decay widths of $h \to \gamma\gamma$, $Z\gamma$ in the MLRSM mentioned in this work.

Table 2. Feynman rules for the SM-like Higgs boson couplings with charged Higgs bosons.

Vertex	Coupling: λ_{hSS}
$\lambda_{hH_1^+H_1^-}$	$2\left\{c_\beta^4\lambda_1 + 2c_\beta^2 s_\beta^2[\lambda_1 - 2(2\lambda_2+\lambda_3)] + \lambda_1 s_\beta^4\right\} v$
$\lambda_{hH_2^+H_2^-}$	$\frac{1}{2}(2\alpha_1 + \alpha_3 + 8\alpha_2 c_\beta s_\beta)v$
$\lambda_{hH_1^{++}H_1^{--}}$	$[\alpha_1 + s_\beta(4\alpha_2 c_\beta + \alpha_3 s_\beta)]v$
$\lambda_{hH_2^{++}H_2^{--}}$	$[\alpha_1 + s_\beta(4\alpha_2 c_\beta + \alpha_3 s_\beta)]v$
$\lambda_{hH_1^{++}H_2^{--}}$	$(\alpha_6 + \alpha_4 c_\beta s_\beta)(-1+2s_\beta^2)\frac{v}{s_\beta}$
$\lambda_{hH_2^{++}H_1^{--}}$	$(\alpha_6 + \alpha_4 c_\beta s_\beta)(-1+2s_\beta^2)\frac{v}{s_\beta}$

The couplings of h with SM fermions can be determined using the Yukawa Lagrangians given in Eq. (7), where the Feynman rule is $-i\left(Y_{h\bar{f}fL}P_L + Y_{h\bar{f}fR}P_R\right)$ for each vertex $h\bar{f}f$. Because this model does not have exotic charged fermions and the couplings of SM leptons to neutral Higgs/gauge bosons ($g_{h\bar{f}f}, g_{Z\bar{f}f}$) are defined as in the SM [36–38], we will use the SM results for one-loop fermion contributions to the decay amplitudes of $h \to Z\gamma, \gamma\gamma$.

The Higgs–gauge boson couplings giving one-loop contributions to the decays $h \to Z\gamma, \gamma\gamma$ are derived from the kinetic Lagrangian of the Higgs bosons, namely

$$
\begin{aligned}
\mathcal{L}^H_{\text{kin}} &= \mathcal{L}_\Phi + \mathcal{L}_{\Delta_L} + \mathcal{L}_{\Delta_R} \\
&= \sum_{i,j=1}^{2} g_{\mu\nu} g_{hW_iW_j} h W_i^{-\mu} W_j^{+\nu} \\
&\quad + \sum_{S_i,j}\left[-ig^*_{hSW_j} W_j^{-\mu}\left(S_i^{+Q}\partial_\mu h - h\partial_\mu S_i^{+Q}\right) + ig_{hSW_j} W_j^{+\mu}\left(S_i^{-Q}\partial_\mu h - h\partial_\mu S_i^{-Q}\right)\right] \\
&\quad + \sum_{S_i,S_j} ig_{ZS_iS_j} Z^\mu\left(S_i^{-Q}\partial_\mu S_j^{Q} - S_j^{Q}\partial_\mu S_i^{-Q}\right) \\
&\quad + \sum_{S_i,j}\left[ig_{ZW_jS_i} Z^\mu W_j^{+\nu} S_i^{-Q} g_{\mu\nu} + ig^*_{ZW_jS_i} Z^\mu W_j^{-\nu} S_i^{Q} g_{\mu\nu}\right] \\
&\quad + \sum_{S_i} ieQA^\mu\left(S_i^{-Q}\partial_\mu S_i^{Q} - S_i^{Q}\partial_\mu S_i^{-Q}\right) + \ldots,
\end{aligned}
\tag{32}
$$

where $S_i, S_j = H^\pm_{1,2}, H^{\pm\pm}_{1,2}$ denote charged Higgs bosons in the MLRSM. The Feynman rules for the h couplings to at least one charged gauge boson are shown in Table 3. The momenta appearing in the vertex factors are $\partial_\mu h \to -ip_{0\mu} h$ and $\partial_\mu S_{i,j} \to -ip_\mu S_{i,j}$, where p_0, $p_\pm$ are incoming momenta.

The Feynman rules for Z couplings to charged Higgs and gauge bosons as in Eq. (32) are given in Table 4. The couplings $g_{ZH_i^{+,++}H_j^{-,--}}$, $g_{ZW_2^+H_{i,j}^-}$ are zero in the MLRSM.

The triple gauge couplings of Z and photon to $W^\pm_{1,2}$ are derived from the kinetic Lagrangian of the non-Abelian gauge bosons

$$
\mathcal{L}^k_g = -\frac{1}{4}\sum_{a=1}^{3}\left[F^a_{L\mu\nu}F_L^{a\mu\nu} + F^a_{R\mu\nu}F_R^{a\mu\nu}\right], \tag{33}
$$

Table 3. Feynman rules for couplings of the SM-like Higgs boson to charged Higgs and gauge bosons.

Vertex	Coupling
$g_{hW_1^+W_1^-}$	$\frac{1}{2}\left\{-4g_Lg_Rs_\beta c_\beta s_\xi c_\xi + (c_\xi^2 g_L^2 + g_R^2 s_\xi^2)\right\} v$
$g_{hW_2^+W_2^-}$	$\frac{1}{2}\left\{4g_Lg_Rs_\beta c_\beta s_\xi c_\xi + (s_\xi^2 g_L^2 + g_R^2 c_\xi^2)\right\} v$
$g_{hW_1^+W_2^-}$	$\frac{1}{2}\left\{s_\xi c_\xi(-g_L^2 + g_R^2) + 2g_Lg_Rs_\beta c_\beta(-c_\xi^2 + s_\xi^2)\right\} v$
$g_{hW_2^+W_1^-}$	$\frac{1}{2}\left\{s_\xi c_\xi(-g_L^2 + g_R^2) + 2g_Lg_Rs_\beta c_\beta(-c_\xi^2 + s_\xi^2)\right\} v$
$g_{hH_1^-W_1^+}$	$\frac{1}{2}g_R s_\xi(c_\beta^2 - s_\beta^2)$
$g_{hH_1^-W_2^+}$	$\frac{1}{2}g_R c_\xi(c_\beta^2 - s_\beta^2)$

Table 4. Feynman rules of couplings of Z to charged Higgs and gauge bosons. Notations p_+ and p_- are incoming momenta.

Vertex	Coupling
$g_{ZH_1^+H_1^-}$	$\frac{1}{2}(p_+ - p_-)[c_{z_2}c_{z_3}g_L - g_R(c_Rc_{z_3}s_{z_2} + s_Rs_{z_3})]$
$g_{ZH_2^+H_2^-}$	$g'(p_+ - p_-)(-c_{z_3}s_Rs_{z_2} + c_Rs_{z_3})$
$g_{ZH_1^{++}H_1^{--}}$	$(p_{++} - p_{--})(c_{z_2}c_{z_3}g_L - c_{z_3}g's_Rs_{z_2} + c_Rg's_{z_3})$
$g_{ZH_2^{++}H_2^{--}}$	$(p_{++} - p_{--})(c_Rc_{z_3}g_Rs_{z_2} + c_{z_3}g's_Rs_{z_2} - c_Rg's_{z_3} + g_Rs_Rs_{z_3})$
$g_{ZW_1^+H_1^-}$	$\frac{1}{2}c_{z_2}c_{z_3}g_Lg_R(c_\beta^2 - s_\beta^2)s_\xi v$
$g_{ZW_1^+H_2^-}$	$\frac{1}{2}c_\xi c_{z_2}c_{z_3}g_Lg_R(c_\beta^2 - s_\beta^2)v$

Table 5. Feynman rules for triple gauge couplings relating with the decay $h \to Z\gamma$.

Vertex	Coupling
$g_{ZW_1^{+\nu}W_1^{-\lambda}}$	$\frac{-e}{s_{z_2}c_Rc_{z_2}}\left[c_Rc_{z_3}(-c_{z_2}^2 + s_\xi^2) + s_Rs_{z_3}s_{z_2}s_\xi^2\right]$
$g_{ZW_2^{+\nu}W_2^{-\lambda}}$	$\frac{e}{s_{z_2}c_Rc_{z_2}}\left[c_Rc_{z_3}(s_\xi^2 - s_{z_2}^2) - s_Rs_{z_3}s_{z_2}c_\xi^2\right]$
$g_{ZW_1^{+\nu}W_2^{-\lambda}}$	$-\frac{es_\xi c_\xi}{s_{z_2}c_Rc_{z_2}}\left[c_{z_3}c_R + s_Rs_{z_3}s_{z_2}\right]$
$g_{ZW_2^{+\nu}W_1^{-\lambda}}$	$-\frac{es_\xi c_\xi}{s_{z_2}c_Rc_{z_2}}\left[c_{z_3}c_R + s_Rs_{z_3}s_{z_2}\right]$

where $F^a_{L,R\mu\nu} = \partial_\mu W^a_{L,R\nu} - \partial_\nu W^a_{L,R\mu} + g_{L,R}\epsilon^{abc}W^b_{L,R\mu}W^c_{L,R\mu}$, and ϵ^{abc} $(a, b, c = 1, 2, 3)$ are the $SU(2)$ structure constants. The respective Z couplings to $W^\pm_{1,2}$ are included in the following part:

$$\mathcal{L}^{ZW^+W^-} \supset -g_L\epsilon^{abc}\left(\partial_\mu W^a_{L\nu}\right)W^{b\mu}_L W^{c\nu}_L - g_R\epsilon^{abc}\left(\partial_\mu W^a_{R\nu}\right)W^{b\mu}_R W^{c\nu}_R. \tag{34}$$

Then, the vertex factors corresponding to particular couplings are defined as

$$\begin{aligned}\mathcal{L}^g_D \to &-g_{ZW_iW_j}Z^\mu(p_0)W_i^{+\nu}(p_+)W_j^{-\lambda}(p_-) \times \Gamma_{\mu\nu\lambda}(p_0, p_+, p_-),\\ &- eA^\mu(p_0)W_i^{+\nu}(p_+)W_i^{-\lambda}(p_-) \times \Gamma_{\mu\nu\lambda}(p_0, p_+, p_-),\end{aligned} \tag{35}$$

where $\Gamma_{\mu\nu\lambda}(p_0, p_+, p_-) \equiv g_{\mu\nu}(p_0 - p_+)_\lambda + g_{\nu\lambda}(p_+ - p_-)_\mu + g_{\lambda\mu}(p_- - p_0)_\lambda$, and $i, j = 1, 2$. The photon always couples to two identical particles as the consequence of the Ward Identity [39], see the second line of Eq. (35). The nonzero factors for triple couplings of Z with charged gauge bosons are collected in Table 5.

To end this section, we emphasize that all couplings determined in this section do not use the assumption $k_1 \gg k_2$, equivalently $t_\beta \gg 1$ as used in Refs. [29,30].

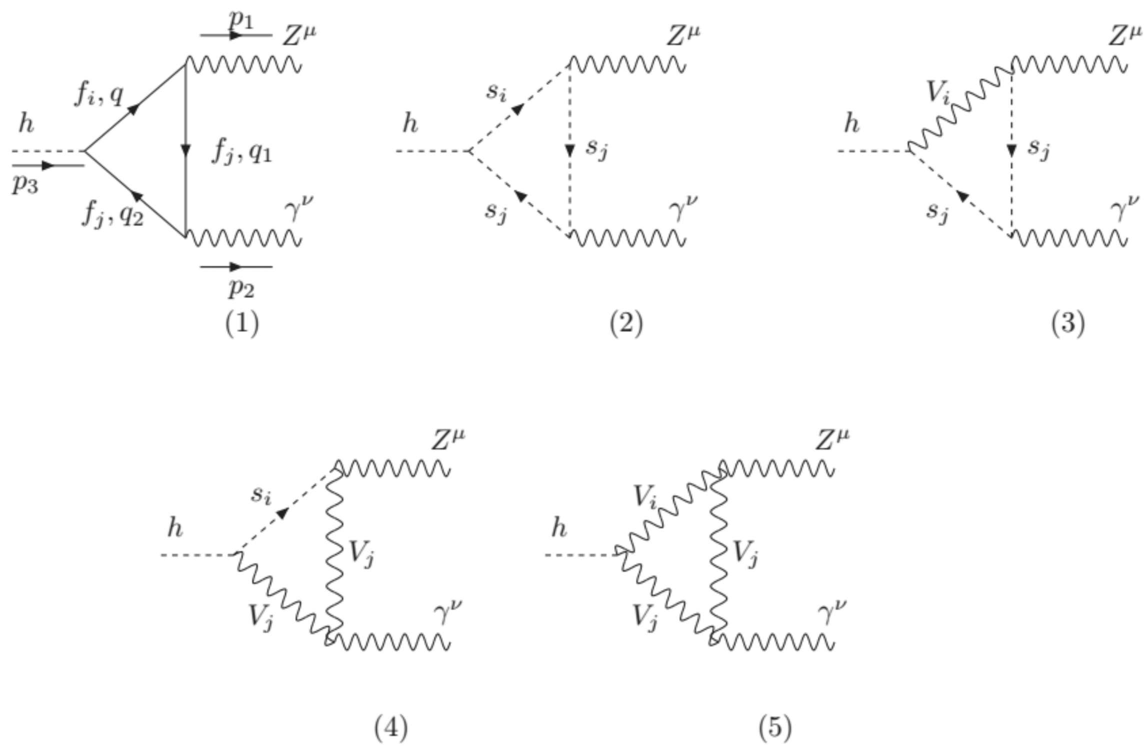

Fig. 1. One-loop three-point Feynman diagrams contributing to the decay $h \to Z\gamma$ in the unitary gauge, where $f_{i,j}$ are the SM fermions, $s_{i,j} = H^{\pm}_{1,2}, H^{\pm\pm}_{1,2}$, $V_{i,j} = W^{\pm}_1, W^{\pm}_2$.

3.2. *Partial decay widths and signal strengths of the decays $h \to Z\gamma, \gamma\gamma$*

In the MLRSM framework, one-loop three-point Feynman diagrams giving contributions to the decay amplitude $h \to Z\gamma$ are shown in Fig. 1, where the unitary gauge is applied to determine the gauge boson contributions. The fermion contributions to the amplitude of the decay $h \to Z\gamma$ coincide with the SM results calculated in Refs. [36,37]. Using the general calculation introduced in Ref. [35], we can write these contributions as follows:

$$F^{\rm LR}_{21,f} = F^{\rm SM}_{21,f} = \sum_{f_i = e_i, u_i, d_i} F^{\rm SM}_{21,f_i}, \tag{36}$$

where all form factors $F^{\rm SM}_{21,f_i}$ are written in terms of the Passarino–Veltman (PV) notations [40].

Similarly, the contribution from the charged Higgs bosons can be given as

$$F^{\rm LR}_{21,S} = F_{21,H_1^+} + F_{21,H_2^+} + F_{21,H_{122}^+} + F_{21,H_{211}^+} + F_{21,H_1^{++}} + F_{21,H_2^{++}} + F_{21,H_{122}^{++}} + F_{21,H_{211}^{++}}. \tag{37}$$

The charged gauge boson contributions $W^{\pm}_{1,2}$ to the $h \to Z\gamma$ amplitude are

$$F^{\rm LR}_{21,V} = F^{\rm LR}_{21,W_1^+} + F^{\rm LR}_{21,W_2^+} + F^{\rm LR}_{21,W_{122}^+} + F^{\rm LR}_{21,W_{211}^+}. \tag{38}$$

Similarly, the contribution from the charged Higgs and gauge bosons arising from diagrams 3 and 4 in Fig. 1 can be given as

$$F^{\rm LR}_{21,VS} = F^{\rm LR}_{21,WSS} + F^{\rm LR}_{21,SWW}, \tag{39}$$

where

$$F^{\rm LR}_{21,WSS} = F^{\rm LR}_{21,W_1^+H_1^+H_1^+} + F^{\rm LR}_{21,W_1^+H_2^+H_2^+} + F^{\rm LR}_{21,W_2^+H_1^+H_1^+} + F^{\rm LR}_{21,W_2^+H_2^+H_2^+}, \tag{40}$$

$$F^{\mathrm{LR}}_{21,SWW} = F^{\mathrm{LR}}_{21,H_1^+W_1^+W_1^+} + F^{\mathrm{LR}}_{21,H_1^+W_2^+W_2^+} + F^{\mathrm{LR}}_{21,H_2^+W_1^+W_1^+} + F^{\mathrm{LR}}_{21,H_2^+W_2^+W_2^+}. \tag{41}$$

Now, the $h \to Z\gamma$ partial decay width is [41,42]:

$$\Gamma^{\mathrm{LR}}(h \to Z\gamma) = \frac{m_h^3}{32\pi} \times \left(1 - \frac{m_Z^2}{m_h^2}\right)^3 \left|F^{\mathrm{LR}}_{21}\right|^2, \tag{42}$$

where the scalar factors F^{LR}_{21} are derived as follows [35]:

$$F^{\mathrm{LR}}_{21} = F^{\mathrm{LR}}_{21,f} + F^{\mathrm{LR}}_{21,S} + F^{\mathrm{LR}}_{21,V} + F^{\mathrm{LR}}_{21,VS}. \tag{43}$$

We note that $F^{\mathrm{LR}}_{21,VS}$ were omitted in some previous works [5,17,18] because their contributions were expected to be much smaller than the contributions from the SM and are still far from the sensitivity of recent experiments. However, since collider sensitivities have recently been improved and new scales have been established, these contributions are necessary. The branching ratio $\mathrm{Br}^{\mathrm{LR}}(h \to Z\gamma)$ in the MLRSM framework is

$$\mathrm{Br}^{\mathrm{LR}}(h \to Z\gamma) = \frac{\Gamma^{\mathrm{LR}}(h \to Z\gamma)}{\Gamma^{\mathrm{LR}}_h}, \tag{44}$$

where Γ^{LR}_h is the total decay width of the SM-like Higgs boson h [41,42]. Although experimental measurements of the SM-like Higgs boson productions and decays are available [43], we focus only on the Higgs production through the gluon fusion process ggF at the LHC, in which the respective signal strengths predicted by the two models SM and MLRSM are equal. Then the signal strength corresponding to the decay mode $h \to Z\gamma$ predicted by the MLRSM is:

$$\mu^{\mathrm{LR}}_{Z\gamma} \equiv \frac{\mathrm{Br}^{\mathrm{LR}}(h \to Z\gamma)}{\mathrm{Br}^{\mathrm{SM}}(h \to Z\gamma)}, \tag{45}$$

where $\mathrm{Br}^{\mathrm{SM}}(h \to Z\gamma)$ is the SM branching ratio of the decay $h \to Z\gamma$. The recent $ggF \to h \to Z\gamma$ signal strength is $\mu_{Z\gamma} = 2.4 \pm 0.9$ at 2.7σ (standard deviation) [2,3].

Similarly, the partial decay width and signal strength of the decay $h \to \gamma\gamma$ can be calculated as [35,42]:

$$\Gamma^{\mathrm{LR}}(h \to \gamma\gamma) = \frac{m_h^3}{64\pi} \times \left|F^{\mathrm{LR}}_{\gamma\gamma}\right|^2,$$

$$\mu^{\mathrm{LR}}_{\gamma\gamma} \equiv \frac{\Gamma^{\mathrm{LR}}(h \to \gamma\gamma)}{\Gamma^{\mathrm{SM}}(h \to \gamma\gamma)}, \tag{46}$$

where

$$F^{\mathrm{LR}}_{\gamma\gamma} = \sum_f F^{\mathrm{LR}}_{\gamma\gamma,f} + \sum_s F^{\mathrm{LR}}_{\gamma\gamma,s} + \sum_v F^{\mathrm{LR}}_{\gamma\gamma,v}, \tag{47}$$

and

$$F^{\mathrm{LR}}_{\gamma\gamma,f} = F^{\mathrm{SM}}_{\gamma\gamma,f} = \sum_{f_i=e_i,u_i,d_i} F^{\mathrm{SM}}_{\gamma\gamma,f_i},$$

$$F^{\mathrm{LR}}_{\gamma\gamma,S} = F_{\gamma\gamma,H_1^+} + F_{\gamma\gamma,H_2^+} + F_{\gamma\gamma,H_1^{++}} + F_{\gamma\gamma,H_2^{++}},$$

$$F^{\mathrm{LR}}_{\gamma\gamma,V} = F_{\gamma\gamma,W_1^+} + F_{\gamma\gamma,W_2^+}. \tag{48}$$

Here we have used notations to the effect that [6]:

$$
\begin{aligned}
F^{\rm SM}_{\gamma\gamma,f_i} &= -\frac{e^2\,Q_{f_i}^2\,N_c}{2\pi^2}\left(m_f Y_{h\bar{f}fL}\right)[4X_2+C_0],\\
F_{\gamma\gamma,s} &= \frac{e^2\,Q_s^2\lambda_{hss}}{2\pi^2}X_2,\\
F_{\gamma\gamma,v} &= \frac{e^2\,Q_V^2\,g_{hvv}}{4\pi^2}\times\left\{\left(6+\frac{m_h^2}{m_V^2}\right)X_2+4C_0\right\},
\end{aligned}
\tag{49}
$$

where $X_2 = C_{12} + C_{22} + C_2$ and $C_{0,i,ij} \equiv C_{0,i,ij}(0, 0, m_h^2; m_x^2, m_x^2, m_x^2)$ are PV functions [40] with $x = f, s, v$ implying fermions, charged Higgs, and gauge bosons, respectively. Particular forms given in Eq. (49) are defined precisely in Ref. [6]. In the following section, the numerical results will be evaluated using LoopTools [44].

4. Numerical discussions

4.1. *Setup parameters*

In this section, we use the following quantities fixed from experiments [45]: $m_h = 125.38$ GeV, m_W, m_Z, well-known fermion masses, $v \simeq 246$ GeV, the $SU(2)_L$ gauge coupling $g_2 \simeq 0.651$, $\alpha_{\rm em} = 1/137$, $e = \sqrt{4\pi\alpha_{\rm em}}$, $s_W^2 = 0.231$.

The unknown Higgs self-couplings of the MLRSM are $\rho_{1,2,3,4}$, $\alpha_{1,2,3,4,5,6}$, $\lambda_{2,3,4}$. The dependent parameter λ_1 is given by Eq. (27). Some Higgs self-couplings are expressed as functions of the heavy Higgs boson masses, namely

$$
\begin{aligned}
m^2_{H_1^0} &= m^2_{A_1} = m^2_{H_1^\pm} = \frac{\alpha_3 v_R^2}{2\left(2s_\beta^2-1\right)},\\
m^2_{H_2^0} &= m^2_{H_2^\pm} = m^2_{H_1^{\pm\pm}} = m^2_{A_2} = \frac{v_R^2}{2}\left(-2\rho_1+\rho_3\right),\\
m^2_{H_3^0} &= 2\rho_1 v_R^2,\ m^2_{H_2^{\pm\pm}} = 2\rho_2 v_R^2.
\end{aligned}
\tag{50}
$$

Choosing the masses of $m_{H_1^+}$, $m_{H_2^+}$, and $m_{H_1^{++}}$ as free parameters we get

$$
\begin{aligned}
\alpha_1 &= \frac{2m^2_{H_2^+}}{\left(t_\beta^2+1\right)v_R^2},\ \alpha_2 = -\frac{t_\beta m^2_{H_2^+}}{\left(t_\beta^2+1\right)v_R^2},\ \alpha_3 = \frac{2\left(t_\beta^2-1\right)m^2_{H_2^+}}{\left(t_\beta^2+1\right)v_R^2},\\
\alpha_4 &= -\frac{2\alpha_6}{t_\beta},\ \rho_2 = \frac{m^2_{H_2^{++}}}{2v_R^2},\ \rho_3 = 2\rho_1+\frac{2m^2_{H_1^+}}{v_R^2}.
\end{aligned}
\tag{51}
$$

The other free parameters are $\lambda_{2,3,4}$, $\rho_1 = m^2_{H_3^0}/(2v_R^2) > 0$, hence the mixing angle and the gauge boson masses will be at the orders of $\mathcal{O}(v^2/v_R^2)$:

$$g_R = g_L = g_2 = e/s_W,\ g' = \frac{e}{\sqrt{1-2s_W^2}},$$

$$s_\xi = -\frac{s_\beta c_\beta v^2}{v_R^2} \ll 1,\ c_\xi = 1 + \mathcal{O}\left(\frac{v^4}{v_R^4}\right) \simeq 1,$$

$$s_R = \frac{\sqrt{1-2s_W^2}}{c_W},\ c_R = t_W,$$

$$s_{z_2} = s_W,\ c_{z_2} = c_W,$$

$$s_{z_3} = \frac{t_W^2\sqrt{1-2s_W^2}\,v^2}{4c_W^2 v_R^2} \ll 1,\ c_{z_3} = 1 + \mathcal{O}\left(\frac{v^4}{v_R^4}\right) \simeq 1. \tag{52}$$

We note here that the relations given in Eq. (52) are consistent with the SM because the two couplings hW^+W^- and ZW^+W^- are consistent with the SM predictions.

Apart from the limit $g_L = g_R$ chosen in Eq. (52), in various discussions for the more general case $g_R \neq g_L$, which showed that this ratio is allowed in the following range [46,47]:

$$0.65 \leq g_R \leq 1.6, \tag{53}$$

where the lower bound $v_R > 10$ TeV.

A recent study showed a lower bound of $m_{W_R} > 5.5$ TeV is still allowed [31], which gives $v_R \geq 17$ TeV in this case. On the other hand, the constraint of $t_\beta \geq 1.2$ is allowed, while no lower bounds of charged Higgs masses were given; especially in the limit of the phase, α given in Eq. (6) is zero. Various works discuss the constraints of Higgs masses indirectly [48], or directly from the LHC for doubly charged Higgs bosons [49]. The lower bounds are $m_{H^{\pm\pm}} \geq 1080$ GeV. Theoretical constraints were discussed in Ref. [33] for Higgs self-couplings satisfying unitarity bounds and vacuum stability criteria, which will be applied in our numerical investigation.

Based on the above discussion for investigating the significant strengths of the two decays $h \to \gamma\gamma,\ Z\gamma$, the values of unknown independent parameters that we choose here will be scanned in the following ranges:

$$m_{H_1^+},\ m_{H_2^+},\ m_{H_2^{++}} \in [1,\ 20]\ \text{TeV},\ v_R \in [20,\ 60]\ \text{TeV},\ t_\beta \in [1.2,\ 30],$$

$$\lambda_{2,3,4} \in [-10, 10], \tag{54}$$

where the Higgs self-couplings satisfy all theoretical constraints discussed in Ref. [33].

4.2. *Results and discussions*

To express the differences of prediction between the SM and the MLRSM, we define a quantity $\Delta\mu_{Z\gamma}$ as in Ref. [6]:

$$\Delta\mu^{\mathrm{LR}}_{Z\gamma} \equiv \left(\mu^{\mathrm{LR}}_{Z\gamma} - 1\right) \times 100\%, \tag{55}$$

which is constrained by recent experiments as $\Delta\mu_{Z\gamma} = 1.4 \pm 0.9$ [2,3], implying the following 1σ deviation:

$$50\% \leq \Delta\mu^{\mathrm{LR}}_{Z\gamma} \leq 230\%. \tag{56}$$

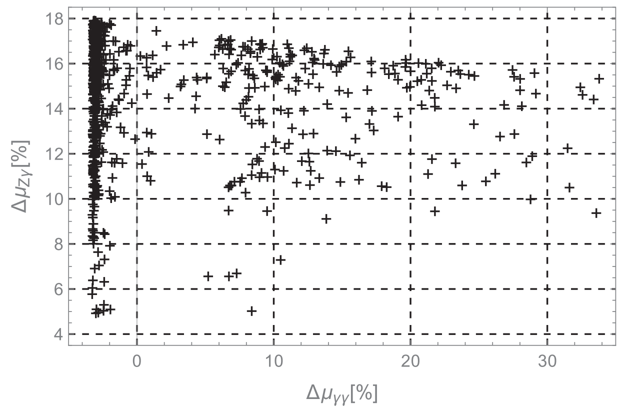

Fig. 2. Correlations between $\Delta\mu_{Z\gamma}^{\rm LR}$ and $\Delta\mu_{\gamma\gamma}^{\rm LR}$ with $g_L = g_R$.

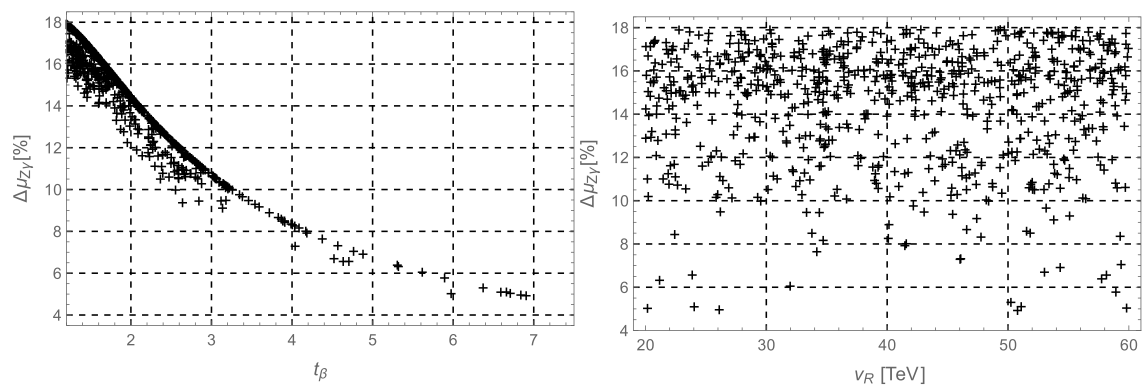

Fig. 3. Correlations between $\Delta\mu_{Z\gamma}^{\rm LR}$ and different values of t_β and v_R with $g_R = g_L$.

The 1σ constraint from $h \to \gamma\gamma$ decay originating from ggF fusion is defined as $\Delta\mu_{\gamma\gamma}^{\rm LR} \equiv (\mu_{\gamma\gamma}^{\rm LR} - 1) \times 100\%$, leading to the respective 2σ deviation as follows:

$$-12\% < \Delta\mu_{\gamma\gamma}^{\rm LR} < 38\%. \tag{57}$$

The numerical results we discuss in the following will always satisfy this constraint. We have checked numerically that the MLRSM always contains regions of the parameter space where both values of $\Delta\mu_{Z\gamma}$, $\Delta\mu_{\gamma\gamma} \to 0$, implying consistency with the SM results. Considering the special case of $g_L = g_R$, we discuss firstly the dependence of $\Delta\mu_{Z\gamma}^{\rm LR}$ on $\Delta\mu_{\gamma\gamma}^{\rm LR}$, which is illustrated in Fig. 2. We just focus on the region satisfying $|\Delta\mu_{Z\gamma}^{\rm LR}| \geq 5\%$ in order to collect interesting points that may support the 1σ range given in Eq. (56). It can be seen that $\Delta\mu_{Z\gamma}^{\rm LR}$ is constrained strictly by $\Delta\mu_{\gamma\gamma}^{\rm LR}$, i.e. $\Delta\mu_{Z\gamma}^{\rm LR} \leq 18\%$ in the range of 2σ deviation given in Eq. (57). It is noted that negative values of $\Delta\mu_{\gamma\gamma}^{\rm LR} < 0$ can give larger $\Delta\mu_{Z\gamma}^{\rm LR}$ than the positive ones. The largest values of $\Delta\mu_{Z\gamma}^{\rm LR}$ are still much smaller than the 1σ deviation given by recent experimental data.

We comment here to make the point that the future sensitivities are $|\Delta\mu_{\gamma\gamma}| \leq 4\%$ and $|\Delta\mu_{Z\gamma}| \leq 23\%$, respectively [23]. In the model under consideration, large values of $\Delta\mu_{Z\gamma} > 23\%$ are not allowed with $g_L = g_R$.

For completeness in the case of $g_L = g_R$, we discuss the dependence of $\Delta\mu_{Z\gamma}^{\rm LR}$ on t_β and v_R, which are shown in Fig. 3. We can see that $\Delta\mu_{Z\gamma}^{\rm LR}$ depends weakly on v_R, but strongly on t_β. Namely, all values of v_R can give large $\Delta\mu_{Z\gamma}^{\rm LR}$, while needing small $t_\beta \to 1.2$.

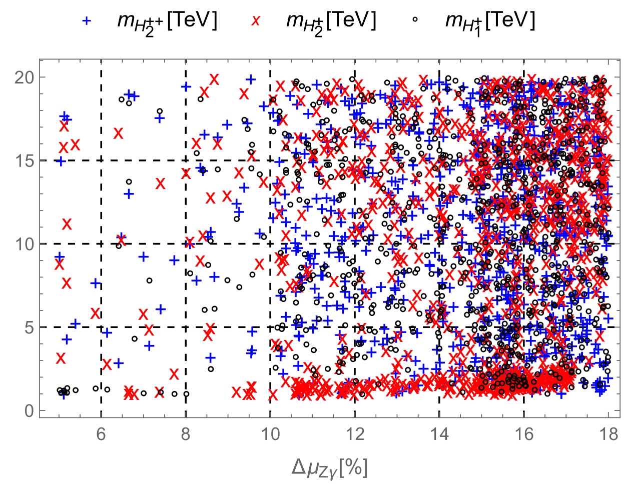

Fig. 4. Correlations between $\Delta\mu^{\rm LR}_{Z\gamma}$ and charged Higgs boson masses with $g_R = g_L$.

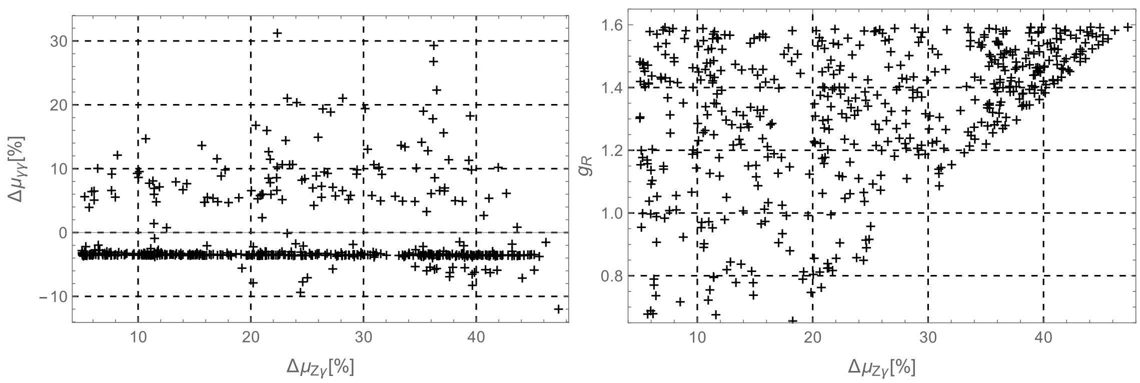

Fig. 5. Correlations between $\Delta\mu^{\rm LR}_{Z\gamma}$ and $\Delta\mu^{\rm LR}_{\gamma\gamma}$ (g_R) in the left (right) panel with $0.65 \leq g_R \leq 1.6$.

The correlations between $\Delta\mu^{\rm LR}_{Z\gamma}$ and charged Higgs boson masses are shown in Fig. 4. The results show that all charged Higgs masses do not affect strongly the values of $\Delta\mu^{\rm LR}_{Z\gamma}$.

Finally, we consider the general case of g_R with allowed values given in Eq. (53). Numerical results for important correlations of $\Delta\mu^{\rm LR}_{Z\gamma}$ with $\Delta\mu^{\rm LR}_{\gamma\gamma}$ and g_R are depicted in Fig. 5. It can be seen clearly that large $\Delta\mu^{\rm LR}_{Z\gamma}$ corresponds to large g_R, which is consistent with the property that new contributions consist of the factor g_R in the Feynman rules shown in Sect. 3. We emphasize that large g_R is necessary for large $\Delta\mu^{\rm LR}_{Z\gamma}$ that can reach a value of 46%, very close to the recent experimental sensitivity. Furthermore, the expected sensitivity of $\Delta\mu^{\rm LR}_{Z\gamma} = 4\%$ does not affect large values of $\Delta\mu^{\rm LR}_{Z\gamma}$ that are visible for the incoming experimental sensitivity of 23%.

Finally, we focus on the correlations of $\Delta\mu^{\rm LR}_{Z\gamma}$ with t_β, v_R, and all charged Higgs masses, which are depicted in Fig. 6. It is seen again that large $\Delta\mu^{\rm LR}_{Z\gamma}$ requires small t_β. In contrast, $\Delta\mu^{\rm LR}_{Z\gamma}$ depends weakly on charged Higgs boson masses and v_R as given in Eq. (54).

5. Conclusions

We have studied all one-loop contributions to the SM-like Higgs decays $h \to \gamma\gamma$, $Z\gamma$ in the MLRSM framework. Interesting properties of the new gauge and Higgs bosons were explored. Namely, the SM-like Higgs couplings were identified with the SM prediction and experimental data. All masses, physical states of gauge and Higgs bosons, and their mixing were presented

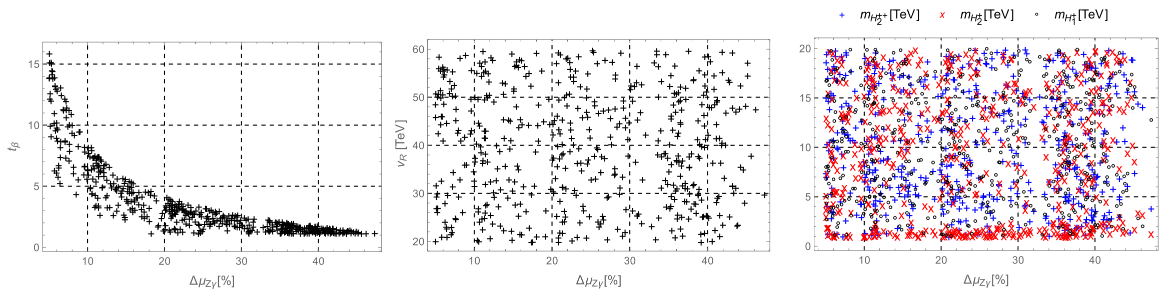

Fig. 6. Correlations of $\Delta\mu^{\mathrm{LR}}_{Z\gamma}$ with t_β, v_R, and charged Higgs masses with $0.65 \leq g_R \leq 1.6$.

clearly so that all couplings related to one-loop contributions to the decay amplitudes $h \to \gamma\gamma$, $Z\gamma$ are derived analytically. From this, the decays $h \to \gamma\gamma$, $Z\gamma$ in the MLRSM have been discussed using the relevant recent experimental results. The one-loop contributions from the diagrams containing both gauge and Higgs mediation were included in the decay amplitude $h \to Z\gamma$. These contributions were ignored in previous studies, although they may enhance the $h \to Z\gamma$ amplitude, but do not affect the $h \to \gamma\gamma$ one, leading to the possibility that large $\Delta\mu_{Z\gamma}$ may be allowed under the strict experimental constraint of $\Delta\mu_{\gamma\gamma}$. We have shown that the mentioned h decay rates depend weakly on t_β, the $SU(2)_R$ vacuum scale v_R. The 2σ deviation of $\mu_{\gamma\gamma}$ results in a rather strict constraint $\left|\Delta\mu_{Z\gamma}\right| \leq 46\%$. On the other hand, large values of $\Delta\mu_{Z\gamma} > 23\%$ can appear under the very strict constraint of $|\Delta\mu_{\gamma\gamma}| \leq 4\%$ corresponding to the future experimental sensitivities, provided the two requirements of sufficiently small t_β and large g_R are met. Therefore, the future experimental searches of the two decays mentioned in this work will be important to constrain the parameter space of the MLRSM.

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