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DTU Journal of Science and Technology 5(48) (2021) 70-78
TRƯỜNG ĐẠI HỌC DUY TÂN
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One-loop contributions to $\mathrm{H} \to Z^* \gamma \to \nu_e \nu_e \gamma$ in standard model

Đóng góp tích phân Feynman một vòng cho quá trình phân rã hạt vô hướng Higgs $\mathrm{H} \to Z^* \gamma \to \nu_e \nu_e \gamma$ trong mô hình chuẩn

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(Ngày nhận bài: 11/6/2021, ngày phản biện xong: 20/9/2021, ngày chấp nhận đăng: 14/10/2021)

Abstract

One-loop contributions to the decay process $\mathrm{H} \to Z^* \gamma \to \nu_e \nu_e \gamma$ in standard model are performed in this paper. The detailed computations are carried out in unitary gauge. In physical results, we present numerical results for partial decay width and its distribution. We find that the partial decay width is given to 0.466 KeV. This result is in the upper bound of the current experimental data at the Large Hadron Collider.

Keywords: Higgs phenomenology; One-loop corrections; analytic methods for Quantum Field Theory; Dimensional regularization.

Tóm tắt

Trong bài báo này, chúng tôi tính các đóng góp tích phân Feynman một vòng cho quá trình phân rã hạt vô hướng Higgs $\mathrm{H} \to Z^* \gamma \to \nu_e \nu_e \gamma$ trong mô hình Chuẩn. Tính toán chi tiết được xét trong chuẩn unitary. Trong phần kết quả vật lý, chúng tôi trình bày kết quả của bề rộng phân rã và các phân bố của bề rộng phân rã cho quá trình trên. Kết quả bề rộng phân rã nhận được từ tính toán này là 0.466 KeV và phù hợp với dữ liệu thực nghiệm hiện tại ở máy gia tốc LHC.

Từ Khóa: Hiện tượng luận hạt vô hướng Higgs; Bổ chính lượng tử; Phương pháp giải tích cho Lý Thuyết trường lượng tử; Phương pháp chỉnh thứ nguyên.

1. Introduction

After the discovery of the Standard model like (SM-like) Higgs boson at the Large Hadron Collider (LHC), one of the main targets at the High-Luminosity Large Hadron Collider (HL-LHC) as well as future colliders [1, 2, 3] is to measure the SM-like Higgs properties. It means that all couplings of the Higgs to gauge bosons and matter particles are probed as precise as possible. From the experimental data, we can

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verify the Standard model at higher energy region as well as extract the contributions of new physics. In all the Higgs decay modes, the channel of Higgs boson decay to photon and missing energy is great of interest the colliders [4, 5, 6, 7, 8, 9] by following reasons: (i) since many new particles which are absent in SM may exchange in the loop diagrams of the decay process; (ii) new neutral particles rather than three neutrinos may exist in new physics. Subsequently, the decay could provide an important information for testing Higgs sector as well as probing to dark matter and constraining new physic parameters.

In order to analyse new physics, we must understand fully the Standard model background. Therefore, precise calculations for $\mathrm{H}\to Z^*\gamma \to \nu_e\nu_e\gamma$ are necessary. The relevant Feynman diagrams for this decay channel start not at tree level but at one-loop level in the electroweak interaction. As the above reasons, we carry out one-loop contributions to the decay $\mathrm{H}\to Z^*\gamma \to \nu_e\nu_e\gamma$. The calculations are performed in unitary gauge by using dimensional regularization. In phenomenological results,we present the partial decay width and its distribution in detail. The partial decay width is to 0.466 KeV which is in the upper bound of the present experimental data at the LHC. Detailed analytical calculations and physical results for $\mathrm{H}\to \nu_l\nu_l\gamma$ with $\mathrm{l}=\mathrm{e},\ \mu,\tau$ are discussed in our forthcoming paper.

Our paper is organized as follows: In section 2, after describing briefly one-loop tensor reduction method, detailed calculations for one-loop contributions to $\mathrm{H}\to Z^*\gamma \to \nu_e\nu_e\gamma$ are explained more. Analytic formulas for one-loop form factors and phenomenological results are presented in this section. Conclusions and outlook are devoted in section 3.

2. Calculations

In general, one-loop amplitude for the decay is expressed $\mathrm{H}\to Z^*\gamma \to \nu_e\nu_e\gamma$in terms of one-loop Feynman tensor integrals which are reduced frequently into scalar functions. In this computation, we apply the tensor reduction method in [10]. The approach will be explained briefly in the following paragraphs. Firstly, the definitions for one-loop one-, two-, three-point tensor integrals with rank P are given by

$$\{A;B;C\}^{\mu_1\mu_2\cdots\mu_P} = (\mu^2)^{2-d/2}\int \frac{d^dk}{(2\pi)^d}\frac{k^{\mu_1}k^{\mu_2}\cdots k^{\mu_P}}{\{D_1;D_1D_2;D_1D_2D_3\}}. \quad (1)$$

Where the inverse Feynman propagators are given as follows:

$$D_j = (k+q_j)^2 - m_j^2 + i\rho, \quad (2)$$

for $\mathrm{j}=1,\cdots,3$. In this equation, $\mathrm{q}_j = \sum_{i=1}^{j} p_i$ with p_i are the external momenta and m_j are internal masses in the loops. Note that $\mathrm{p}_1+p_2+p_3=0$ thanks to momentum conservation. Space-time dimension is $\mathrm{d}=4-2\varepsilon$ and μ^2 parameter is a renormalization scale.

The explicit reduction formulas for one-loop one-, two- and three-point tensor integrals up to rank $\mathrm{P}=2$ involving this process are then shown as follows [10]:

$$\begin{aligned}
A^{\mu} &= 0, \\
A^{\mu\nu} &= g^{\mu\nu} A_{00}, \\
B^{\mu} &= q^{\mu} B_1, \\
B^{\mu\nu} &= g^{\mu\nu} B_{00} + q^{\mu} q^{\nu} B_{11}, \\
C^{\mu} &= q_1^{\mu} C_1 + q_2^{\mu} C_2 = \sum_{i=1}^{2} q_i^{\mu} C_i, \\
C^{\mu\nu} &= g^{\mu\nu} C_{00} + \sum_{i,j=1}^{2} q_i^{\mu} q_j^{\nu} C_{ij} \\
&= g^{\mu\nu} C_{00} + q_1^{\mu} q_1^{\nu} C_{11} + q_2^{\mu} q_2^{\nu} C_{22} + (q_1^{\mu} q_2^{\nu} + q_2^{\mu} q_1^{\nu}) C_{12} \quad (\text{where } C_{12} = C_{21}).
\end{aligned} \tag{3}$$

In the above relations, we have utilized the short notation [10] $\{g, q_i\}^{\mu\nu\rho} = g^{\mu\nu} q_i^{\rho} + g^{\nu\rho} q_i^{\mu} + g^{\mu\rho} q_i^{\nu}$. All scalar coefficients $A_{00}, B_1, \cdots, C_{22}$ are so-called Passarino-Veltman functions (PV) in [10]. Analytic formulas of the PV functions are well-known and they have been implemented into package **LoopTools** [12] for numerical computations.

2.1 Analytic results

The detailed evaluations for the decay $H(p) \to \nu_e(q_1)\nu_e(q_2)\gamma(q_3)$ in unitary gauge in which only the physical particles appear and ghosts and Goldstone bosons being absent are presented in this subsection. The decay channel consists of W boson and fermion internal particles exchanging in one-loop triangle diagrams (seen Fig. 1 and Fig. 2 respectively). The fermion and gauge boson propagators related to the decay in unitary gauge and the relevant Feynman rules for the three- and four-point vertices which we use for this work are summarized and devoted in Appendix. The Ward identity is implied for external photon's on-shell condition as $q_3^{\nu} \epsilon_{\nu}^{*} = 0$ where q_3^{ν}, ϵ_{ν}^{*} are momentum and polarization vector of photon respectively. Besides that Dirac equation's conditions for external electron neutrinos $\nu_e(q_1)$ and $\nu_e(q_2)$ are applied as to simplify more the calculations. Kinematic invariant variables for this decay process are given
$p^2 = M_H^2, \quad q_1^2 = m_{\nu_e}^2, \quad q_2^2 = m_{\nu_e}^2,$
$q_3^2 = m_{\gamma}^2 = 0,$ with M_H being the Higgs boson mass.

Assuming that electron neutrinos are massless, so that $q_1^2 = q_2^2 = 0$, we then introduce the following Mandelstam variables as:

$$\begin{aligned}
q_{12} &= q^2 = (q_1 + q_2)^2 = 2q_1 \cdot q_2, \qquad q_{13} = (q_1 + q_3)^2 = 2q_1 \cdot q_3. \\
q_{23} &= (q_2 + q_3)^2 = 2q_2 \cdot q_3 = M_H^2 \quad q_{12} q_{13}.
\end{aligned} \tag{4}$$

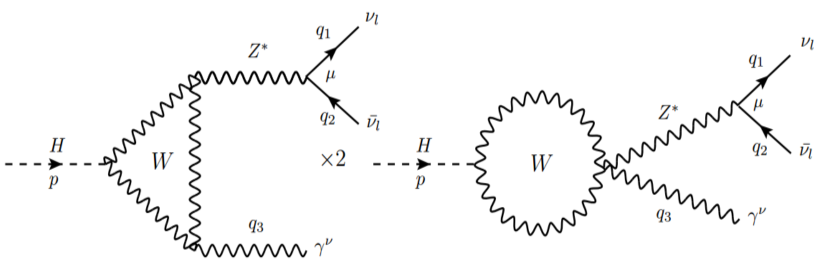

Figure 1: W-boson particles exchanging in one-loop triangle diagrams of $H \to \nu_e \nu_e \gamma$ in unitary gauge.

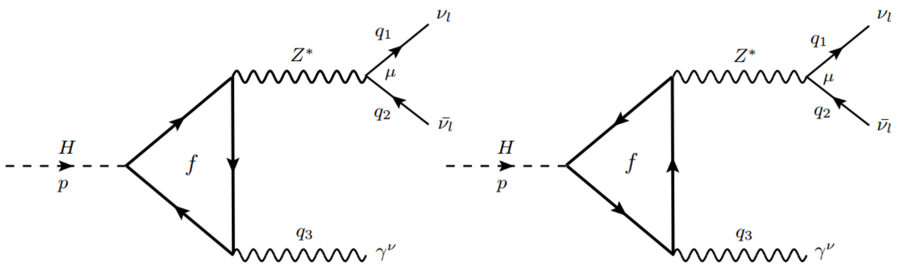

Figure 2: Fermion particles f exchanging in one-loop triangle diagrams of $H \rightarrow \nu_e \nu_e \gamma$ in unitary gauge.

General one-loop amplitude for the decay channel can be written as follows:

$$\mathcal{A} = \mathcal{A}_{\rm tri}^{(W)} + \mathcal{A}_{\rm tri}^{(f)}. \quad (5)$$

In this formula, $A_{\rm tri}^{(W)}$ presents for the contributions of triangle Feynman diagrams with W boson internal lines (shown in Fig. 1). The term $A_{\rm tri}^{(f)}$ is to the contributions of triangle Feynman diagrams with fermions exchanging in the loop (seen in Fig. 2). Each component of Eq. (5) is expressed in terms of Lorentz invariant structure as follows:

$$\mathcal{A}_{\rm tri}^{(W/f)} = \Big[F_1^{(W/f)} q_3^\mu q^\nu + F_2^{(W/f)} g^{\mu\nu}\Big] u(q_1)\gamma^\mu P_L v(q_2)\epsilon_\nu^*(q_3). \quad (6)$$

Where we have used left-handed projection operator $P_L = (1 \quad \gamma_5)/2$. The calculations are consistently straightforward and we make full usage of `Package X` [13, 14] for handling all Dirac traces and contracts in general d dimensions. The form factors $F_1^{(W/f)}$ and $F_2^{(W/f)}$ are expressed in terms of scalar coefficients - more specifically, in terms of Passarino-Veltman functions at arbitrary d are obtained by summing all diagram amplitudes of each type as follows. In the limit $d \rightarrow 4$, all scalar Passarino-Veltman coefficients $A_{00}, B_1, \cdots, C_{22}$ of the mentioned form factors are expressed in terms of the Passarino-Veltman function's basis such as one-point integrals A_0, two-point integrals B_0 and three-point integrals C_0 in [10]. In principle, each diagram's contribution can be dependent of ultraviolet cut-off ($1/\varepsilon$-term) and the mass scale parameter of dimensional regularization μ^2 when taking $d \rightarrow 4$, we confirm that these terms are cancelled out after summing all diagrams. As a result, the total amplitude contributions become consistently finite at $d{=}4$ and are independent of μ^2. Taking an example, one-loop triangle amplitude's contributions related to this decay channel, in particularly, consist of the ultraviolet divergences that appear in the scalar two-points integrals B_0 and their own expressions in terms of $1/\varepsilon$ in dimensional regularization. When we take into considerations about difference between two B_0 's, the analytical result becomes finite in terms of logarithm functions at $d{=}4$. Specifically, we obtain for $M = m_f, M_W$ and $P^2 = q_{12}, M_H^2$ as follows

$$\begin{aligned} B_0(M_H^2, M^2, M^2) - B_0(q_{12}, M^2, M^2) = \\ = \frac{\sqrt{M_H^4 - 4M^4 M_H^2}}{M_H^2} \ln\left[\frac{\sqrt{M_H^4 - 4M^4 M_H^2} + 2M^4 - M_H^2}{2M^4}\right] \\ - \frac{\sqrt{q_{12}^2 - 4M^4 q_{12}}}{q_{12}} \ln\left[\frac{\sqrt{q_{12}^2 - 4M^4 q_{12}} + 2M^4 - q_{12}}{2M^4}\right], \end{aligned} \quad (7)$$

$$B_0(P^2, M^2, M^2) - B_0(0, M^2, M^2) = \\ = 2 + \frac{\sqrt{P^4 - 4M^4P^2}}{P^2} \ln\left[\frac{\sqrt{P^4 - 4M^4P^2} + 2M^4 - P^2}{2M^4}\right]. \quad (8)$$

Moreover, the three-point integral related to this decay channel is also given by finite result in terms of logarithm functions at $\mathrm{d}=4$ as follows:

$$C_0(0, q_{12}, M_H^2, M^2, M^2, M^2) = \frac{1}{2(M_H^2 - q_{12})} \times \\ \times \left\{ \ln^2\left[\frac{\sqrt{M_H^4 - 4M^4M_H^2} + 2M^4 - M_H^2}{2M^4}\right] - \ln^2\left[\frac{\sqrt{q_{12}^2 - 4M^4q_{12}} + 2M^4 - q_{12}}{2M^4}\right]\right\}. \quad (9)$$

By performing explicitly ε-expansion for the above form factors, we confirm exactly Ward identity relation for the $q_3^\mu q^\nu$ and $g^{\mu\nu}$-term's form factors. Therefore, the analytical results at space-time dimension $\mathrm{d}=4$ in terms of logarithm functions of related masses and Mandelstam variables for above form factors in Eq. (6) are expressed as

$$\begin{aligned} F_1^{(W)} &= \frac{M_H^2 - q_{12}}{2} F_2^{(W)} \\ &= -\frac{\alpha^2}{2M_H^2 M_W^3 s_W^3 (M_H^2 - q_{12})^2 (q_{12} - M_Z^2 + i\Gamma_Z M_Z)} \times \\ &\times \Bigg\{ M_H^2 M_W^2 \left[M_H^2(q_{12} - 6M_W^2) + 12M_W^4 + 6M_W^2 q_{12} - 2q_{12}^2\right] \times \\ &\qquad \times \ln^2\left[\frac{-M_H^2 + \sqrt{M_H^4 - 4M_H^2M_W^2} + 2M_W^2}{2M_W^2}\right] \\ &+ M_H^2 \Big\{ 2M_H^4 M_W^2 - M_H^4 q_{12} + 12M_H^2 M_W^4 - 4M_H^2 M_W^2 q_{12} \\ &\quad + \sqrt{q_{12}^2 - 4M_W^2 q_{12}} \left[M_H^2(q_{12} - 2M_W^2) + 2M_W^2(q_{12} - 6M_W^2)\right] \times \\ &\qquad \times \ln\left[\frac{-q_{12} + \sqrt{q_{12}^2 - 4M_W^2 q_{12}} + 2M_W^2}{2M_W^2}\right] \\ &\quad - M_W^2 \left[M_H^2(q_{12} - 6M_W^2) + 12M_W^4 + 6M_W^2 q_{12} - 2q_{12}^2\right] \times \\ &\qquad \times \ln^2\left[\frac{-q_{12} + \sqrt{q_{12}^2 - 4M_W^2 q_{12}} + 2M_W^2}{2M_W^2}\right] \\ &\quad + M_H^2 q_{12}^2 - 12M_W^4 q_{12} + 2M_W^2 q_{12}^2 \Big\} \\ &+ q_{12}\sqrt{M_H^4 - 4M_H^2 M_W^2} \left[M_H^2(2M_W^2 - q_{12}) + 12M_W^4 - 2M_W^2 q_{12}\right] \times \\ &\qquad \times \ln\left[\frac{-M_H^2 + \sqrt{M_H^4 - 4M_H^2M_W^2} + 2M_W^2}{2M_W^2}\right] \Bigg\} \end{aligned} \quad (10)$$

and

$$\begin{aligned} F_1^{(f)} &= \frac{M_H^2 - q_{12}}{2} F_2^{(f)} \\ &= \frac{\alpha^2 m_f^2 N_C^f Q_f}{2M_H^2 M_W c_W^2 s_W^3 (M_H^2 - q_{12})^2 (q_{12} - M_Z^2 + i\Gamma_Z M_Z)} (T_f^3 - 2Q_f s_W^2) \times \\ &\times \Bigg\{ M_H^2 \Bigg[(4m_f^2 - M_H^2 + q_{12}) \ln^2 \left[\frac{-q_{12} + \sqrt{q_{12}^2 - 4q_{12}m_f^2} + 2m_f^2}{2m_f^2} \right] \\ &\quad + 4\sqrt{q_{12}^2 - 4q_{12}m_f^2} \ln \left[\frac{-q_{12} + \sqrt{q_{12}^2 - 4q_{12}m_f^2} + 2m_f^2}{2m_f^2} \right] - 4M_H^2 + 4q_{12} \Bigg] \\ &\quad + M_H^2 (M_H^2 - 4m_f^2 - q_{12}) \ln^2 \left[\frac{-M_H^2 + \sqrt{M_H^4 - 4m_f^2 M_H^2} + 2m_f^2}{2m_f^2} \right] \\ &\quad - 4q_{12} \sqrt{M_H^4 - 4M_H^2 m_f^2} \ln \left[\frac{-M_H^2 + \sqrt{M_H^4 - 4m_f^2 M_H^2} + 2m_f^2}{2m_f^2} \right] \Bigg\}. \end{aligned} \tag{11}$$

Here α is the fine-structure constant, $c_W = \cos\theta_W = M_W/M_Z$ and $s_W = \sin\theta_W = \sqrt{1-(M_W/M_Z)^2}$ with θ_W is the electroweak mixing angle. In addition m_f, N_C^f, Q_f and T_f^3 are the mass, the color multiplicity factor ($N_C^f = 1$ for leptons and $N_C^f = 3$ for quarks), the charge (in units of *e*), and the third component of weak isospin of the fermion f respectively.

The decay width is then calculated as follow:

$$\frac{d\Gamma}{dE_\gamma d\cos\theta} = \frac{M_H^2 E_\gamma^3 (M_H - 2E_\gamma)}{128\pi^3} \left| F_1^{(W)} + \sum_f F_1^{(f)} \right|^2 (1 + \cos^2\theta). \tag{12}$$

Where E_γ is the photon energy and θ is angle of photon and electron neutrino in center-of-mass of neutrino pair. Note that due to the couplings of the Higgs boson to fermions are proportional to the fermion masses, so we only take into considerations about the top quark t, bottom quark b, strange quark s, charm quark c and tau lepton τ masses for the charged fermion f loop diagrams.

2.2 Numerical results

In this paper, we use the following input parameters: $\alpha = 1/137.035999084$, $M_Z = 91.1876$ GeV, $\Gamma_Z = 2.4952$ GeV, $M_W = 80.379$ GeV, $M_H = 125.1$ GeV, $m_\tau = 1.77686$ GeV, $m_t = 172.76$ GeV, $m_b = 4.18$ GeV, $m_s = 0.93$ GeV and $m_c = 1.27$ GeV, we gain numerical result for the decay width. Integrating over $E_\gamma \in [0, M_H/2]$ and $\cos\theta \in [-1, 1]$, we get the decay width $\Gamma = 0.466$ KeV. This result is in the bound of experimental data at the LHC.

In this Fig. 3, the distribution of decay width as a function of E_γ and $\cos\theta$ is shown. We observe the peak which are corresponding to the Z-pole that Z boson decay to neutrinos. The position of this peak for $\theta \in [-\pi, \pi]$ is located at

$$E_\gamma = \frac{M_H^2 - M_Z^2}{2M_H} = 29.3159\,\text{GeV}. \tag{13}$$

This provides important information for testing SM at higher energy regions at LHC.

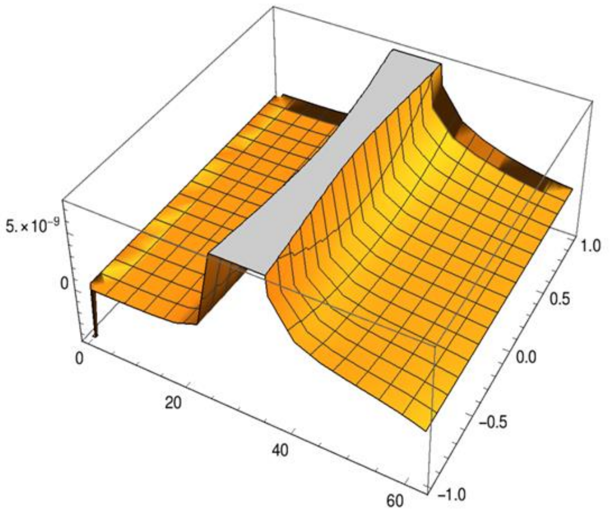

Figure 3: Differential decay width as a function of E_γ and $\cos\theta$.

3. Conclusions

Analytic results for one-loop contributions to $H\to Z^*\gamma \to \nu_e\nu_e\gamma$ have presented in this paper. In physical results, we compute the partial decay width and differential decay width with respect to photon's energy. The partial decay width is 0.466 KeV. This result agrees with upper bound of experimental data at LHC.

Acknowledgment

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under the grant number $103.01-2019.346$.

Appendix: Feynman rules and Feynman diagrams

The fermion f, virtual Z,W gauge boson propagators and the Feynman rules for the three-point and four-point vertices in unitary gauge are, respectively, given. In the Tables, we use $P_L = (1-\gamma_5)/2$.

The short notation for the standard Lorentz tensors of the gauge boson self couplings $\Gamma_{\mu\nu\lambda}(p_1,p_2,p_3) = g_{\mu\nu}(p_1-p_2)_\lambda + g_{\lambda\nu}(p_2-p_3)_\mu + g_{\mu\lambda}(p_3-p_1)_\nu$ with momenta are all inward and $S_{\mu\nu,\alpha\beta} = 2g_{\mu\nu}g_{\alpha\beta} - g_{\mu\alpha}g_{\nu\beta} - g_{\mu\beta}g_{\nu\alpha}$ are introduced for convenience. The notation $P_Z(p) = 1/(p^2 - M_Z^2 + iM_Z\Gamma_Z)$ from the propagator of the virtual Z^* gauge boson is used.

Particle types	Propagators
fermions f	$i\dfrac{\not{k}+m_f}{k^2-m_f^2}$
W boson	$\dfrac{-i}{p^2-M_W^2}\left(g^{\mu\nu}-\dfrac{p^\mu p^\nu}{M_W^2}\right)$
Virtual Z boson	$-iP_Z(p)\left(g^{\mu\nu}-\dfrac{p^\mu p^\nu}{M_Z^2}\right)$

Table 1: Feynman rules involving the decay $H\to Z^*\gamma\to\nu_e\nu_e\gamma$ through fermions and W bosons loop in the unitary gauge.

Vertices	**Couplings**
$H \cdot W_\mu^+ \cdot W_\nu^-$	$ie\frac{M_W}{s_W}g_{\mu\nu}$
$A_\mu(p_1) \cdot W_\nu^+(p_2) \cdot W_\lambda^-(p_3)$	$-ie\Gamma_{\mu\nu\lambda}(p_1, p_2, p_3)$
$Z_\mu(p_1) \cdot W_\nu^+(p_2) \cdot W_\lambda^-(p_3)$	$-ie\frac{c_W}{s_W}\Gamma_{\mu\nu\lambda}(p_1, p_2, p_3)$
$Z_\mu \cdot A_\nu \cdot W_\alpha^+ \cdot W_\beta^-$	$-ie^2\frac{c_W}{s_W}S_{\mu\nu,\alpha\beta}$
$H \cdot f \cdot \bar{f}$	$-ie\frac{m_f}{2s_W M_W}$
$A_\mu \cdot f \cdot \bar{f}$	$ieQ_f\gamma_\mu$
$Z_\mu \cdot f \cdot \bar{f}$	$i\frac{e}{s_W c_W}\gamma_\mu\left(T_f^3 P_L - s_W^2 Q_f\right)$
$H \cdot l^+ \cdot l^-$	$-ie\frac{m_l}{2s_W M_W}$
$A_\mu \cdot l^+ \cdot l^-$	$-ie\gamma_\mu$
$Z_\mu \cdot \nu_e \cdot \bar{\nu}_e$	$i\frac{e}{2s_W c_W}\gamma_\mu P_L$
$W_\mu \cdot l \cdot \nu_l$	$i\frac{e}{\sqrt{2}s_W}\gamma_\mu P_L$

Table 2: Couplings involving the decay H$\rightarrow Z^*\gamma \rightarrow \nu_e\nu_e\gamma$ through fermions and W bosons loop in unitary gauge.

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