Exact formulae for Higgs production through $e\gamma \rightarrow eH$ in the non-linear $R_\xi$-gauge

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We study the production of the SM Higgs boson ($H^0$) at future $e\gamma$ colliders, through the reaction $e\gamma \rightarrow eH^0$. The amplitude is evaluated using the non-linear $R_\xi$-gauge, which greatly simplifies the calculation. Complete analytical expressions for the amplitudes are presented, which include the contributions from 1-loop triangles $\gamma\gamma^*H^0$ and $\gamma^*Z^*H^0$ as well as the W- and Z-boxes with their related $eeH^0$ triangle graphs. The resulting cross section for this mechanism indicates that it could be used to detect the Higgs signal and to test its properties.

I. INTRODUCTION

The search for the standard Model (SM) Higgs boson at future colliders, has become the focus of extensive studies, mainly because of its importance as a test of the mechanism of electroweak symmetry breaking [1]. At the next $e^+e^-$ linear collider (NLC), it will be possible to study some features of the SM Higgs boson ($H^0$), through the production reactions $e^+e^- \rightarrow HZ$, and $e^+e^- \rightarrow H\gamma$ [3,4]. However, given the prospect for studying $e\gamma$ collisions at the NLC through its operation in the photon mode [5], it is convenient to have a production mechanism that can be used to study the detection of the Higgs boson in this mode. Besides the interest to detect a Higgs boson in any machine, it is important to study carefully the possibility to test its couplings to all the SM particles, since this will help to determine whether it corresponds to the SM or to some of its extensions.

In this paper, we calculate the cross-section for the reaction $e\gamma \rightarrow He$, using a nonlinear $R_\xi$-gauge [10–13]. We present complete analytical expressions for the amplitudes, and show the power of the non-linear gauge in verifying the gauge invariance of the result. In this gauge some 3-point vertices $WVG$, as well as some 4-point vertices $WVGH$, are absent; $V$ represents the neutral gauge bosons $Z, A$ and $G^\pm$ denotes the charged Goldstone boson. Thus, the number of diagrams is reduced considerably.

In order to derive the Feynman rules arising from the nonlinear $R_\xi$ gauge, one needs to specify the gauge fixing term, which has the form [3]

$$\mathcal{L}_{GF} = -\frac{1}{2\xi_Y} (f^Y)^2 - \frac{1}{2\xi_i} (f^i)^2,$$

where the SU(2)$_L$ and U(1)$_Y$ $f$-functions are given by:

$$f^i = \left[ \delta^{i\mu} \partial_\mu - gB_\mu \epsilon^{ij}\right] W^{j\mu} + ig\xi_i \left[ \phi^i \frac{\tau_i}{2} \langle \phi \rangle - \langle \phi^i \rangle \frac{\tau_i}{2} \phi^i + i\epsilon^{ij3} \phi^j \frac{\tau_i}{2} \phi^i \right], \quad (2)$$

$$f^Y = \partial_\mu B^\mu + ig\xi_Y \left[ \phi^Y \frac{1}{2} \langle \phi \rangle - \langle \phi^Y \rangle \frac{1}{2} \phi^Y \right], \quad (3)$$

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respectively, with $\langle \phi \rangle_0 = \frac{1}{\sqrt{2}} (0, v)$ denoting the v.e.v. of the neutral component of the Higgs doublet and $\phi' = \phi - \langle \phi \rangle_0$. Using now the definitions: $f^\pm = \frac{t^2 \mp i f^2}{\sqrt{2}}, \quad f^Z = c_W f^3 - s_W f^Y, \quad f^A = c_W f^3 + s_W f^Y, \quad c_W = \cos \theta_W, \quad s_W = \sin \theta_W$, one obtains:

\begin{align}
    f^+ &= (\partial_\mu - ig B_\mu) W^{+\mu} + ig (\xi_1 - \xi_2) G_W^+(v + H^0 + i G_Z) - i g (\xi_1 + \xi_2) G_W^+(v + H^0 - i G_Z), \\
    f^Z &= \partial_\mu Z^{\mu} - (c_W^2 \xi_3 + s_W^2 \xi_Y) M_Z G_Z, \\
    f^A &= \partial_\mu A^{\mu} - \frac{s_W}{2} (\xi_3 - \xi_Y) M_Z G_Z.
\end{align}

The gauge parameters $\xi_Y, \xi_\lambda$ are all chosen to be unity, which defines the non-linear 't Hooft-Feynman gauge. After substituting these expressions in the gauge-fixing lagrangian, and including them in the full gauge and Higgs lagrangian, one derives the non-linear vertices for the scalar and gauge-sector, which are summarized in ref. [8].

The diagrams encountered in the calculation of the $e^- \gamma \to e^- H^0$ include: i) graphs with the triangle $AA^* H$ and $AZ^* H$ loop (Fig. 1a), ii) graphs with $W^-$ and $Z^-$ mediated box diagrams and the related triangles with external fermion legs (Figs. [9], [10], [11], and ii) those with $Z-A$ and $Z-H$ self energies (Figs. [12], [13]). It results that these sets are separately gauge invariant. The diagrams of Figs. [12] involves a virtual gauge bosons ($Z^0$ or $\gamma$) in the t-channel. The relevant contributions to these triangle graphs include the heaviest fermions (the top and bottom quarks), $W^{\pm}, G^{\pm}$ bosons and ghosts, however the amplitudes for each subset are also separately gauge invariant, thus the total amplitude is also gauge invariant. The remaining diagrams (Figs. [13], [14], [15]) have no gauge boson poles. They consist of box diagrams, with the Higgs boson emerging from one of the box vertices, together with associated triangle diagrams $e e H^0$. There are two such combinations of boxes and triangles: one with $Z$'s in the loops and one with $W$'s in the loops. The amplitude for the graphs of Fig. 1-e, which consist of tadpole and bubble diagrams, with fermions, $W^{\pm}, G^{\pm}$ bosons and ghosts in the loops, combine to give vanishing results, which is a consequence of using the non-linear gauge. On the other hand, the amplitude for the graphs of Fig. 1-f vanish in the approximation $m_e = 0$.

We have evaluated the amplitudes using dimensional regularizaton, with the help of the programs Feyncalc [14] and the numerical package FF [15]. Our result for the total amplitude is written as follows:

\begin{equation}
    \mathcal{M} = \mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_W^{\text{box}} + \mathcal{M}_Z^{\text{box}}.
\end{equation}

The contribution to the matrix element from the $A-$ and $Z-$triangles is given by:

\begin{equation}
    \mathcal{M}_{\gamma,Z} = \frac{i \alpha^2 M_W}{48 s_W^2 c_W} \pi(p_2)(a_{\gamma,Z} - b_{\gamma,Z} \gamma_5)\gamma^\nu u(p_1)\epsilon^\mu(k_1, \lambda_1) F_{\gamma,Z}(k_1 \cdot k_2 g_{\mu\nu} - k_1 \nu k_2 \mu),
\end{equation}

where

\begin{align}
    F_{\gamma} &= \frac{4 s_W^2 c_W^4}{M_W^2 (t - M_Z^2)} \left\{ 2 N_c Q_f^2 H_f + \frac{\gamma W}{\lambda W - \tau W} (2 + 7 \tau W) \left[ B_0 (M_H^2, M_W^2, M_{\frac{1}{2}}^2) - B_0 (t, M_W^2, M_{\frac{1}{2}}^2) \right] \right. \\
    &\quad + 2 + 3 \tau W + \left( 2 + 3 \tau W + 8 \frac{\tau W - \lambda W}{\lambda W} \right) 2 M_W^2 C_0 (t, M_H^2, M_{\frac{1}{2}}^2) \right\},
\end{align}

\begin{align}
    F_Z &= \frac{c_W^4}{M_W^2 (t - M_Z^2)} \left\{ - \frac{C_f^2 N_c Q_f H_f}{c_W^2} + 4 (3 - t_W^2) M_W^2 C_0 (t, M_H^2, M_{\frac{1}{2}}^2) \right. \\
    &\quad + \frac{\tau W \lambda W}{2(\tau W - \lambda W)} \left[ 5 + \frac{2}{\tau W} + \left( 1 + \frac{2}{\tau W} \right) t_W^2 \right] \left\{ 1 - \frac{\tau W}{2} \left[ B_0 (M_H^2, M_W^2, M_{\frac{1}{2}}^2) - B_0 (t, M_W^2, M_{\frac{1}{2}}^2) \right] \\
    &\quad + 2 M_W^2 C_0 (t, M_H^2, M_{\frac{1}{2}}^2) \right\} \right\}.
\end{align}

The function $H_f$ represents the fermion contribution to the loops and is given by:

\begin{equation}
    H_f = \frac{\tau_f \lambda_f}{\tau_f - \lambda_f} - \frac{\lambda_f \tau_f^2}{(\tau_f - \lambda_f)^2} \left[ B_0 (M_H^2, M_L^2, M_{\frac{1}{2}}^2) - B_0 (t, M_L^2, M_{\frac{1}{2}}^2) \right] + 2 \left( 1 + \frac{\tau_f \lambda_f}{\tau_f - \lambda_f} \right) M_L^2 C_0 (t, M_H^2, M_{\frac{1}{2}}^2),
\end{equation}
with

\[ a_\gamma = 1, \quad b_\gamma = 0, \quad a_Z = 1 - 4s_W^2, \quad b_Z = 1, \]
\[ \tau_x = \frac{4M_Z^2}{M_H^2}, \quad \lambda_x = \frac{4M_Z^2}{M_H^2}, \quad t_x = \frac{4a}{c_x}. \]  

(10)

Although one can write analytical expressions for the previous \( B_0 \) and \( C_0 \) scalar functions, they are also evaluated with the help of the FF package. The full dependence of the above \( C_0 \)'s is the following:

\[ C_0(t, M_H^2, M_W^2) = C_0(0, t, M_H^2, M_W^2), \]  

(11a)

\[ C_0(t, M_H^2, M_W^2) = C_0(0, t, M_H^2, M_W^2). \]  

(11b)

The expression for the amplitude coming from the W-box and its related graph, is the following:

\[ \mathcal{M}_{W}^{box} = \frac{i\alpha^2 M_W}{4s_W^3 c_W} \pi(p_2) \gamma^\nu \left(a_Z - \gamma_5\right)^2 u(p_1) \epsilon^\mu(k_1, \lambda_1) \left[-A(t, s, u) \left(k_1 \cdot p_1 g_{\mu \nu} - p_{1\mu} k_{1\nu}\right) \right. \]
\[ + \left. A(t, u, s) \left(k_1 \cdot p_2 g_{\mu \nu} - p_{2\mu} k_{1\nu}\right) \right], \]  

(12)

with \( s = (p_1 + k_1)^2, \quad t = (k_2 - k_1)^2, \quad u = (k_1 - p_2)^2, \) and

\[ A(t, s, u) = \frac{1}{2st} \left[ \left( \frac{s - M_Z^2}{s} \right) \left(M_Z^2(s + u) - su\right) \right] D_{0Z}(1, 2, 3, 4) \]
\[ + \left( s - M_Z^2 \right) \left[ C_{0Z}(1, 2, 4) + \frac{u}{s} C_{0Z}(1, 2, 3) - \frac{t + u}{s} C_{0Z}(2, 3, 4) \right] \]
\[ + \frac{1}{s} \left( t - s - 2M_Z^2 \frac{st}{(s + t)(s - M_Z^2)} \right) C_{0Z}(1, 3, 4) + \frac{2t}{s + t} \left(B_{0Z}(3, 4) - B_{0Z}(1, 3)\right), \]  

(13)

and the arguments of the scalar functions are

\[ B_{0Z}(1, 3) = B_0(u, m_e^2, M_Z^2), \]  

(14a)

\[ B_{0Z}(3, 4) = B_0(M_H^2, M_Z^2, M_Z^2), \]  

(14b)

\[ C_{0Z}(1, 2, 3) = C_0(0, 0, u, m_e^2, m_e^2, M_Z^2), \]  

(14c)

\[ C_{0Z}(1, 2, 4) = C_0(0, s, 0, m_e^2, m_e^2, M_Z^2), \]  

(14d)

\[ C_{0Z}(1, 3, 4) = C_0(0, M_H^2, u, m_e^2, M_Z^2, M_Z^2), \]  

(14e)

\[ C_{0Z}(2, 3, 4) = C_0(s, 0, M_H^2, M_Z^2, m_e^2, M_Z^2), \]  

(14f)

\[ D_{0Z}(1, 2, 3, 4) = D_0(0, s, M_H^2, u, 0, 0, m_e^2, m_e^2, M_Z^2, M_Z^2). \]  

(14g)

The labels 1, 2, 3, 4 in \( D_0 \) are associated to the internal loop-masses, namely to the last four entries of \( D_0 \). Then, the \( B_0(C_0) \) functions are obtained by suppressing two (one) of the propagators that appear in the \( D_0 \) function.

The expression for the amplitude coming from the W-box and its related \( eeH^0 \) triangle graph is given by:

\[ \mathcal{M}_{W}^{box} = \frac{i\alpha^2 M_W}{2s_W^3} \pi(p_2) \gamma^\nu \left(1 - \gamma_5\right)^2 u(p_1) \epsilon^\mu(k_1, \lambda_1) \left(\left(A_1(t, s, u) + A_2(t, u, s) \right) \left(k_1 \cdot p_1 g_{\mu \nu} - p_{1\mu} k_{1\nu}\right) \right. \]
\[ \left. - \left( A_2(t, s, u) + A_1(t, u, s) \right) \left(k_1 \cdot p_2 g_{\mu \nu} - p_{2\mu} k_{1\nu}\right) \right], \]  

where
\[ A_1(t, s, u) = \frac{1}{2st} \left[ \left( \frac{s - M_W^2}{s} \right) (M_W^2(s + u) + st) D_{0W}(1, 2, 3, 4) \right. \]
\[ \left. + \left( s - M_W^2 \right) \left[ C_{0W}(2, 3, 4) - \frac{t}{s} C_{0W}(1, 3, 4) + \frac{u + t}{s} C_{0W}(1, 2, 4) - \frac{s + u}{s} C_{0W}(1, 2, 3) \right] \right. \]
\[ \left. + \frac{2t}{s + u} [B_{0W}(1, 2) - B_{0W}(1, 3)] \right] , \] (16)

\[ A_2(t, s, u) = \frac{1}{2tu} \left[ \left( \frac{t + u - M_W^2}{u} \right) (M_W^2(s + u) - st) - 2M_W^2 t \right] D_{0W}(1, 2, 3, 4) \]
\[ + \left( t + u - M_W^2 \right) \left[ \frac{s}{u} C_{0W}(2, 3, 4) + \frac{t}{u} C_{0W}(1, 3, 4) - \frac{s + u}{u} C_{0W}(1, 2, 4) + \frac{u^2 - 2tu + t^2}{u(t + u)} C_{0W}(1, 2, 4) \right] \]
\[ + \frac{2t}{t + u} [B_{0W}(2, 4) - B_{0W}(1, 2)] + \frac{2t}{s + u} [B_{0W}(1, 3) - B_{0W}(1, 2)] \right] . \] (17)

The scalar functions that appear before have the following arguments:

\[ B_{0W}(1, 2) = B_0(M_H^2, M_W^2, M_W^2), \] (18a)

\[ B_{0W}(1, 3) = B_0(t, M_H^2, M_W^2), \] (18b)

\[ B_{0W}(2, 4) = B_0(s, 0, M_W^2), \] (18c)

\[ C_{0W}(1, 2, 3) = C_0(t, 0, M_H^2, M_W^2, M_W^2, M_W^2), \] (18d)

\[ C_{0W}(1, 2, 4) = C_0(0, s, M_H^2, M_W^2, 0, M_W^2), \] (18e)

\[ C_{0W}(1, 3, 4) = C_0(0, 0, t, M_W^2, 0, M_W^2), \] (18f)

\[ C_{0W}(2, 3, 4) = C_0(0, 0, s, 0, M_W^2, M_W^2), \] (18g)

\[ D_{0W}(1, 2, 3, 4) = D_0(0, 0, 0, M_H^2, t, s, M_W^2, 0, M_W^2, M_W^2). \] (18h)

In order to obtain the cross-section, one has to square the total amplitude, sum and average over initial and final polarizations, then the correspondent differential cross section for the reaction \( \gamma + e \rightarrow H + e \) is expressed as follows:

\[ \frac{d\tilde{\sigma}}{dt} = \frac{1}{16\pi s^2} |\langle M \rangle|^2 \] (19)

where:

\[ |\langle M \rangle|^2 = \frac{\alpha^4 M_W^4}{64 s_0^4 c_W^4} \left\{ (s^2 + u^2) \left[ f_s^2 + 2a_2Re(F_1 F_7^*) + (1 + a_2^2) |F_7|^2 \right] + s^2 f_s + u^2 f_u \right\} , \] (20)

with

\[ f_s = |A_{12}|^2 + (1 + 6a_2^2 + a_1^2)|A_s|^2 + 2Re(A_{12} F_7^*) - 2(1 + a_2^2)Re(A_s F_7^*) \]
\[ -2(1 + a_2^2)Re(A_{12} F_7^*) + 4(1 + a_2)Re(A_{12} F_7^*) - 2(a_2^2 + 3a_2)Re(A_s F_7^*), \] (21)

with \( f_u = f_s(s \rightarrow u; A_{12} \rightarrow -A_{21}; A_s \rightarrow -A_u), A_s = A(t, s, u), A_u = A(t, u, s) \), and also:

\[ A_{12} = 2c_W^4 \left[ A_1(t, s, u) + A_2(t, u, s) \right] \]
\[ A_{21} = 2c_W^4 \left[ A_2(t, s, u) + A_1(t, u, s) \right]. \] (22)

Finally, in order to obtain the total cross-section (\( \sigma_T \)), one needs to convolute \( \tilde{\sigma} \) with the photon distribution (8), namely
\[ \sigma_T = \frac{1}{S} \int_{M_H^2}^{S_{\text{max}}} F_\gamma\left(\frac{S}{S_{\text{max}}}\right) \hat{s}(s) \, ds, \]  

(23)

where \( S \) denotes the squared c.m. energy of the \( e^+e^- \)-system, and the photon distribution is given by

\[ F_\gamma(x) = \frac{1}{D(\xi)} \left[ 1 - x + \frac{4x}{1 - x(1 - x)} - \frac{4x^2}{\xi^2(1 - x)^2} \right], \]  

(24)

where:

\[ D(\xi) = \left( 1 - \frac{4}{\xi} - \frac{8}{\xi^2} \right) \log(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2} \].  

(25)

We present in Fig. 2 the resulting cross-section for our process. We have taken \( m_t \sim 175 \text{ GeV} \) \cite{17}, and the values for the electroweak parameters given in the table of particle properties \cite{18}. In fact, it happens that the contributions of the boxes can be neglected. Although the cross section is small, about 6 fb for \( m_H = 200 \text{ GeV} \) and \( E_{\text{c.m.}} = 500 \text{ GeV} \), it is larger than the one for the reaction \( e^+e^- \rightarrow H + \gamma \) \cite{4}. With the expected NLC luminosities (100 fb\(^{-1}\)/yr) it will be possible to observe up to about 600 \( H + e \) events, which should allow to study the properties of the Higgs boson. Our results reproduce correctly the value reported in Ref. \cite{4} which uses only the photon-pole contribution, for the total cross-section; we find \( \sigma = 6.1 \text{ fb} \), whereas they find \( \sigma = 5.9 \text{ fb} \), for \( E_{\text{c.m.}} = 500 \text{ GeV} \) and \( M_H = 200 \text{ GeV} \).

The final signature depends on the Higgs boson mass. For instance, if we focus on the intermediate-mass region \((M_W < M_H < 2M_W)\) the dominant Higgs decay is into \( bb \) pairs, and in order to estimate the backgrounds that need to be considered, one could rely on the results of Ref. \cite{4}, which considers the production of \( e\gamma \rightarrow e + bb \) in the context of their study of the production of the pseudoscalar \( A_0 \) of the MSSM, and they conclude that this background can be handled, and detection of the signal is possible. In our case, since the event rates are of the same order, we believe that the signal from \( H^0 \) can be detected too \cite{1}.

In conclusion, we have studied the production of the SM Higgs boson \( (H^0) \) at future \( e\gamma \) colliders, through the reaction \( e\gamma \rightarrow eH^0 \). The amplitude is evaluated using a non-linear \( R_T \)-gauge, which greatly simplifies the calculation, and allows to present complete analytical expressions for the amplitudes. The resulting cross section for this mechanism indicates that it could allow the detection of the Higgs boson, and can also be used to test the Higgs boson properties.

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\[\text{[1] After completion of this work, we became aware that the same calculation has been performed by E. Gabrielli et al. [19], but in the linear gauge. Comparing the number of graphs arising in each method illustrates the power of the non-liner gauge, since the number of graphs that we have evaluated is reduced considerably. Some differences among our works can be noticed, for instance in our paper the cross-section includes folding with the photon distributions, which is not done in their paper. We also agree with Ref. [4], that the Williams-Weizsacker approximation overestimates the exact result, whereas in ref. [12] it is found the opposite.}\]

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**FIG. 1.** Classification of graphs that contributes to the reaction $e\gamma \rightarrow eH^0$.

**FIG. 2.** The cross section for the reaction $e\gamma \rightarrow eH^0$ at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV.
Figure 1:
“Exact formulae for Higgs production ...”
Cross section for the process $e\gamma \rightarrow eH$

Figure 2:
"Exact formulae for Higgs..."