Nonlinear Dynamics and Applications. Vol. 25 (2019) 225 - 230

Single gauge boson production in electron-photon collisions in the set of Standard Model extensions

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The differential and total cross sections of the single gauge boson production in quasielastic high energy electron-photon scattering are obtained within the Standard Model in leading order and next-to-leading order. The anomalous gauge boson coupling in the effective Lagrangian approach were studied. Numerical analysis was performed. The best conditions for registration of generated effects beyond the Standard Model were determined.

PACS numbers: 12.15.Lk, 12.60.Cn, 14.60.Cd
Keywords: photon, electron, gauge boson, electroweak interaction, radiative corrections, linear colliders

1. Introduction

The Standard Model (SM) is the most advanced theory which describes the particles interactions. However, it is obvious that the SM is not the universal model, but only a low-energy approximation of more extensive model. For this reason that most theoretical investigations are realized for the construction and study of various extended models. The most interesting models have a considerable simplicity and predictive power. The study of such models is the purpose of experiments on the linear accelerators of new generation.

The most promising models for research on linear colliders are models that include anomalous triple and quartic gauge boson interactions. From the most general considerations, it is possible to construct a generalized Lagrangian for this kind of interaction, limiting consideration of operators of finite dimension. This approach is called the effective Lagrangian method, which includes not only the operators mentioned above, but also the corresponding new anomalous gauge coupling (AGC) [1, 2].

This paper is devoted to the study of single gauge boson production in electron-photon collisions. These processes [3–6]

$$e^-\gamma \to e^-\gamma, \tag{1}$$
$$e^-\gamma \to e^-Z, \tag{2}$$
$$e^-\gamma \to \nu_e W^-, \tag{3}$$

can be studied with the precise accuracy on linear accelerators of new generation, such as the International Linear Collider (ILC) [7, 8].

We must note that using process (2) it is possible investigation of $Z^*Z\gamma$ and $\gamma^*Z\gamma$ anomalous interactions. The process (3) has an exceptional importance in the studies of triple AGC, since it is the only one that allows to study pure $W^*W\gamma$ anomalous gauge interaction.

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2. Cross sections

2.1. Kinematic

We start from consideration of general process

$$e^-(p, m_e) + \gamma(k, 0) \to C^-(p_1, m_c) + N^0(k_1, m_n), \tag{4}$$

where C^- and N^0 are the final particles (charged and neutral); $p(p_1)$ and $k(k_1)$ are the 4-momenta of initial(final) charged and neutral particles, correspondingly; $m_e(m_c)$ and $0(m_n)$ are their masses.

The expression of the total cross section for the such type of processes can be written as follows:

$$\sigma = \frac{1}{8\pi(s - m_e^2)^2} \int |\mathcal{M}|^2 \, dQ^2, \tag{5}$$

where s and Q^2 are Mandelstam variables:

$$s = (p + k)^2, \tag{6}$$

$$Q^2 = -(p - p_1)^2, \tag{7}$$

$\mathcal{M}$ is process amplitude. Integration can be performed using the following limits:

$$Q^2_\pm = \frac{(s + m_e^2)(s + m_c^2 - m_n^2) \pm (s - m_e^2)\sqrt{\lambda(s, m_c^2, m_n^2)}}{2s} - m_c^2 - m_n^2. \tag{8}$$

2.2. Radiative corrections

The cross section including radiative corrections (RC) can be presented in the following form:

$$\sigma = \sigma^{tree}(1 + \delta), \tag{9}$$

where σ^{tree} is the tree level contribution to the total cross section and δ is relative radiative correction [9].

One-loop corrections contain unphysical ultraviolet (UV) and infrared (IR) divergencies, which are reduced by adding correspondingly counter-term and soft photon bremsstrahlung contributions. The obtained expression depends on the collider energy resolution ΔE.

2.3. Anomalous gauge couplings

Effective lagrangian of anomalous $WW\gamma$ interaction can be presented in following form [10]:

$$\begin{aligned} -\mathcal{L}_{WW\gamma}/e = i\kappa_\gamma W_\mu^\dagger W_\nu F^{\mu\nu} + \\ + \frac{i\lambda_\gamma}{m_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu F^{\nu\lambda} - g_4^\gamma W_\mu^\dagger W_\nu \left(\partial^\mu A^\nu + \partial^\nu A^\mu\right) + \\ + g_5^\gamma \varepsilon^{\mu\nu\rho\sigma} \left(W_\mu^\dagger \overleftrightarrow{\partial}_\rho W_\nu\right) A_\sigma + i\tilde{\kappa}_\gamma W_\mu^\dagger W_\nu \tilde{F}^{\mu\nu} + \frac{i\tilde{\lambda}_\gamma}{m_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu \tilde{F}^{\nu\lambda}, \end{aligned} \tag{10}$$

where F_μ is electromagnetic field tensor, W_μ is W^--boson field, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $\tilde{V}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$, $(A \overleftrightarrow{\partial}_\mu B) = A(\partial_\mu B) - B(\partial_\mu A)$.

Following eq. (10) one can put a vertex function of the form

$$\Gamma_{\gamma}^{\alpha\beta\mu}(q,\overline{q},P) = \frac{\lambda_\gamma}{m_W^2}\left(q_\nu g^{\rho\alpha} - q^\rho g_\nu^\alpha\right)\left(\overline{q}_\rho g_\sigma^\beta - \overline{q}_\sigma g_\rho^\beta\right)\left(P^\sigma g^{\mu\nu} - P^\nu g^{\mu\sigma}\right) + \\ + \frac{\tilde{\lambda}_\gamma}{2m_W^2}\left(q_\nu g^{\rho\alpha} - q^\rho g_\nu^\alpha\right)\left(\overline{q}_\rho g_\sigma^\beta - \overline{q}_\sigma g_\rho^\beta\right)\left(P_\gamma g_\tau^\mu - P^\tau g_\gamma^\mu\right)\varepsilon^{\sigma\nu\gamma\tau} - \\ - \Delta\kappa_\gamma\left(P^\alpha g^{\beta\mu} - P^\beta g^{\alpha\mu}\right) + \tilde{\kappa}_\gamma \varepsilon^{\alpha\beta\mu\nu} P_\nu \quad (11)$$

with CP-odd (λ_γ, $\delta\kappa_\gamma$) and CP-even ($\tilde{\kappa}_\gamma$, $\tilde{\lambda}_\gamma$) AGC. In similar way vertex function of $V^*Z\gamma$ interaction can be presented as

$$\Gamma_{Z\gamma V}^{\alpha\beta\mu}(q_1,q_2,P) = \frac{s - m_V^2}{m_Z^2}\left[h_1^V\left(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{m_Z^2}P^\alpha\left(P\cdot q_2 g^{\mu\beta} - q_2^\mu P^\beta\right) + \right. \\ \left. + h_3^V \varepsilon^{\mu\alpha\beta\rho} q_{2\rho} + \frac{h_4^V}{m_Z^2} P^\alpha \varepsilon^{\mu\beta\rho\sigma} P_\rho q_{2\sigma}\right]. \quad (12)$$

3. Numerical analysis

To carry out numerical analysis, some software is required. The presented results were obtained using the following tools:

- Analytical results: ***Wolfram Mathematica*** system [11];
- Squared matrix elements: ***FormCalc*** package;
- Processes kinematics: ***FeynCalc*** package;
- Passarino-Veltman integration: ***LoopTools*** library [12];
- Numerical integration: ***Vegas*** Monte-Carlo simulator [13].

Unphysical UV- and IR-divergencies parametrization were performed using dimensional regularization. Final results do not depend on t'Hoft-Veltman mass regulator μ^2. On-mass shell regularization scheme was choosed. Following experimental features were used: energy resolution of collider $\Delta E = 0.1\sqrt{s}$, scattered particle angle cut $\Delta\vartheta = 20°$. Anomalous gauge couplings constraints were determined taking into account the following value for standard deviation σ^{SD}:

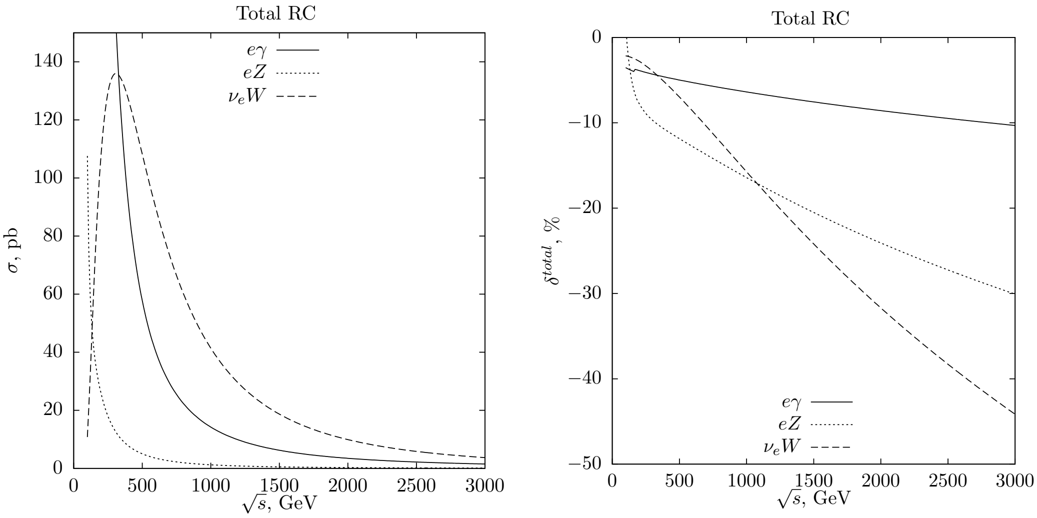
$$\sigma^{SD} = 0.01 \cdot \sigma(s_0) + 1/\mathfrak{L}_{\text{int}}$$

with integrated luminosity $\mathfrak{L}_{\text{int}} = 100$ fb^{-1}.

3.1. Standard Model results

Total cross sections with RC and relative RC are shown in Fig. 1.

With increasing of interaction energy, the absolute value of the cross sections decreases. In case of W boson production cross section has a peak at interactions energy $\sqrt{s}$ =320 GeV with value about 136 pb. RC have principally negative values and reach -43%. At $\sqrt{s}$ =1.5 TeV cross sections don't exceed 20 pb.

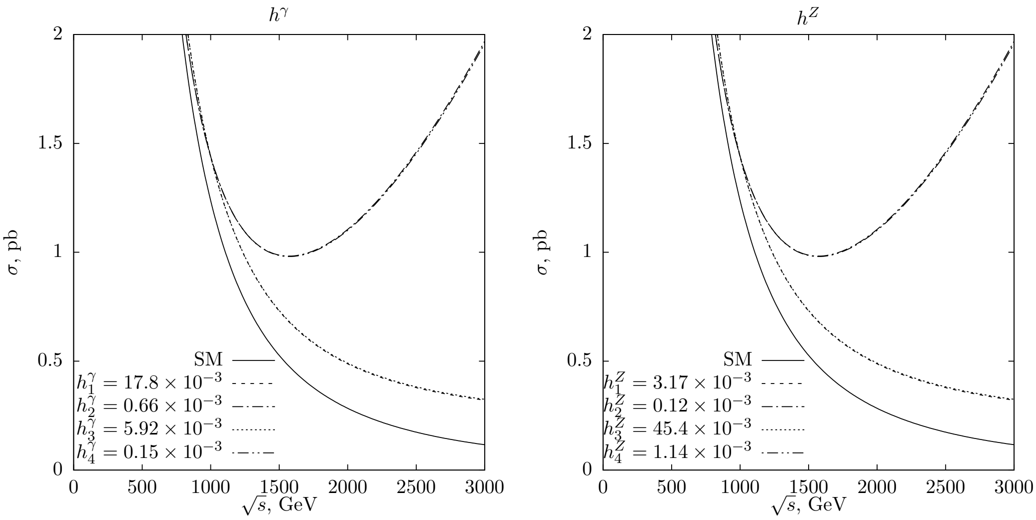


a) b)

Figure 1. The total cross sections including the lowest order radiative corrections a) and relative radiative corrections b) for a set of processes.

3.2. Anomalous interaction results

Anomalous interactions study was performed using ND fit. It means that only N AGC is free and all other have there SM values. Contributions of terms for every $ZV\gamma$ coupling in 1D fit are presented in Fig. 2. As one can see, with increasing of interaction energy the absolute value of couplings with odd indexes increases starting from energy value about 1.5 TeV. This behavior is explained by the presence of a gauge cancellation. Result of 2D fit for pairs of CP-even/odd AGC is presented in Fig. 3.



a) b)

Figure 2: Total cross section of $e\gamma \to eZ$ process obtained using $2\sigma^{SD}$ limits for h_i^γ a) and h_i^Z b)

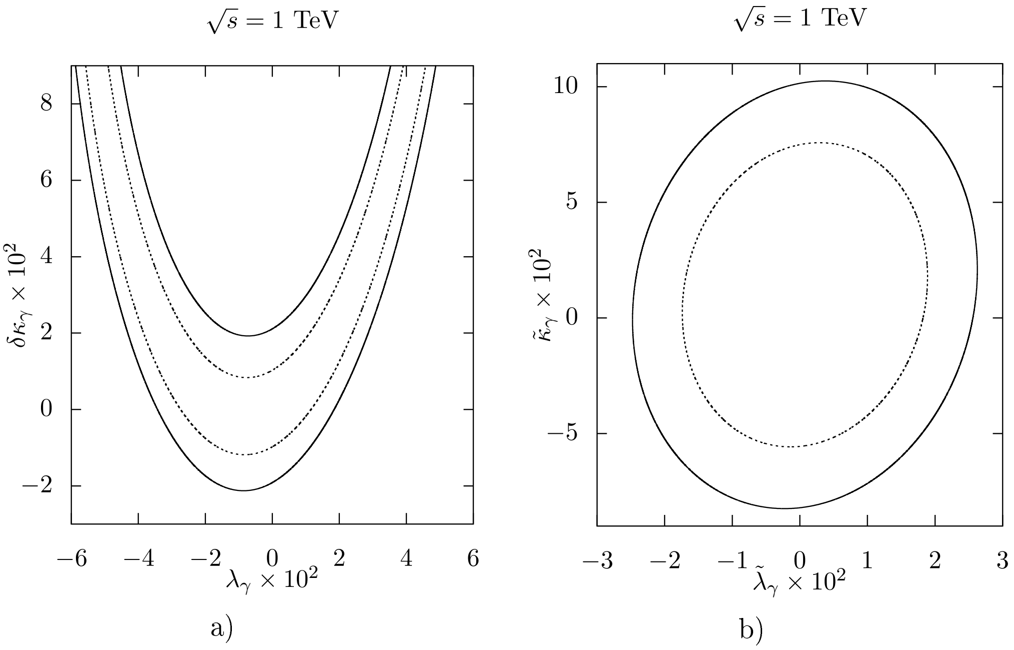


Figure 3. 95% (solid lines) and 68% (dashed lines) C.L. constraints for the following pairs of gauge couplings: $\left(\tilde{\kappa}_\gamma,\, \tilde{\lambda}_\gamma\right)$ a) and $(\delta\kappa_\gamma,\, \lambda_\gamma)$ b)

AGC	LEP	ILC 0.5 TeV	ILC 1.0 TeV
$h_1^\gamma \times 10^3$	[-50, 50]	[-19.10, 19.10]	[-17.79, 17.79]
$h_2^\gamma \times 10^3$	[-40, 20]	[-2.907, 2.907]	[-0.661, 0.661]
$h_3^\gamma \times 10^3$	[-50, 0]	[-6.823, 6.823]	[-5.919, 5.919]
$h_4^\gamma \times 10^3$	[10, 50]	[-0.641, 0.641]	[-0.149, 0.149]
$h_1^Z \times 10^3$	[-120, 110]	[-3.406, 3.406]	[-3.174, 3.174]
$h_2^Z \times 10^3$	[-70, 70]	[-0.519, 0.519]	[-0.118, 0.118]
$h_3^Z \times 10^3$	[-190, 60]	[-52.39, 52.39]	[-45.45, 45.45]
$h_4^Z \times 10^3$	[-40, 130]	[-4.925, 4.925]	[-1.143, 1.143]
$\delta\kappa_\gamma \times 10^3$	[-99, 66]	[-18.78, 19.46]	[-19.14, 21.09]
$\lambda_\gamma \times 10^3$	[-59, 17]	[-64.11, 31.83]	[-34.30, 18.47]
$\tilde{\kappa}_\gamma \times 10^3$	—	[-120.8, 170.3]	[-82.07, 101.5]
$\tilde{\lambda}_\gamma \times 10^3$	—	[-72.23, 83.93]	[-24.75, 25.60]

Table 1: 95% C.L. anomalous gauge couplings limits and LEP experimental data

4. Conclusion

In the paper the differential and total cross sections of the gauge bosons production processes in electron-photon collisions including radiative corrections were calculated. As it was shown by numerical analysis, the contribution of radiative corrections is significant and this strongly affect on the background.

Anomalous gauge boson interactions were studied. Final results are presented in Tab. I. As one can see the large integral luminosity will be able significantly clarify the constraints for AGC on ILC. The most preferable kinematical range for search of deviations from SM is located around W boson production maximum for 4D operators couplings. When interaction energy become higher than 1.5 TeV the contribution of 6D operators is significant.

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