Contribution of the main radiative corrections to anomalous quartic constants in process $\gamma\gamma \rightarrow W^+W^-$

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Abstract

Evaluation of anomalous couplings in the $\gamma\gamma \rightarrow W^+W^-$ process needs to calculate the cross section $\sigma(W^+W^-)$ with a high precision. Therefore one has to consider the main contribution of high order effects. In this paper contributions of anomalous quartic boson interaction given by $\mathcal{L}_0$, $\mathcal{L}_c$, $\mathcal{L}_0$ are analyzed in high-energy region. Influence of high order effects is studied in dependences of $\sigma(W^+W^-)$ on anomalous constants and contour plots with statistical error $2\delta$.

1 Introduction

Linear colliders with centre of mass energies running to 1 TeV gives a hope for the detection of deviations from SM predictions.

The production of two and three electroweak gauge bosons in the high-energy $\gamma\gamma$ collisions allows to check the anomalous quartic gauge boson couplings $a_0$, $a_c$, $\tilde{a}_0$ obtained from the Lagrangians (1) – (3), for more detailed information see refs. [1] – [5]. Quartic gauge boson couplings leads to direct electroweak symmetry breaking, in particular to the scalar sector of the theory or more generally to new physics of electroweak gauge bosons. Since the mechanism of symmetry breaking isn’t revealed completely so anomalous quartic gauge bosons can explain it and provide the first evidence of new physics in this sector of the electroweak theory. The influence of three possible anomalous couplings on the cross sections of $W^+W^-$ productions has been investigated [6] at the TESLA kinematics ($\sqrt{s} \sim 1$ TeV).

Correct consideration of results for $\gamma\gamma \rightarrow W^+W^-$ process and precision analysis of the future experiments data are impossible without calculation of whole set the

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Figure 1: Feynman diagrams of $\gamma\gamma \rightarrow W^+W^-$ accompanied real photon emission

first-order radiative corrections, presented in figs. 1, 2 (see for example refs. [9] – [14]).

Thus at $\sqrt{s} \sim 1\ TeV$ the radiative correction is about a value of Born cross section, it gives contribution to $\sigma^{\text{Born}}(W^+W^-)$ compared with anomalous one. In this paper we focus our attention on the most important QED correction to $\gamma\gamma \rightarrow W^+W^-$. 
Anomalous Lagrangians of quartic boson interaction

In order to construct the structures contained anomalous quartic gauge boson couplings where one photon is involved at least, one has to consider the operators with the lowest dimension of 6 (see refs. [2, 4]). That is required for a custodial $SU(2)_c$ symmetry to have the $\rho = M_W^2 / (M_Z^2 \cos^2 \theta_W)$ parameter close to 1. Thus
the 6-dimensional operators are considered

\[ \mathcal{L}_0 = -\frac{e^2}{16\Lambda^2} a_0 F_{\mu\nu} F^{\mu\nu} \bar{W}_\alpha W^\alpha, \]

\[ \mathcal{L}_c = -\frac{e^2}{16\Lambda^2} a c F^\mu_{\alpha \beta} F^{\mu\nu} \bar{W}^\beta W^\alpha, \]

\[ \tilde{\mathcal{L}}_0 = -\frac{e^2}{16\Lambda^2} \tilde{a}_0 F^\mu_{\alpha \beta} \tilde{F}^{\mu\nu} \bar{W}^\beta W^\alpha, \]

where we introduce the triplet of gauge bosons

\[ \bar{W}_\mu = \left( \frac{1}{\sqrt{2}}(W^+_\mu - W^-_\mu), \frac{i}{\sqrt{2}}(W^+_\mu + W^-_\mu), \frac{1}{\cos \theta_W} Z_\mu \right) \]

and the field-strength tensors

\[ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \]

\[ W^i_\mu = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu, \]

\[ \tilde{F}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}. \]

The scale Λ is introduced to keep the coupling constant \( a_i \) dimensionless. In practice, the Λ are specified in the frame of the chosen model for new physics that supports anomalous quartic gauge boson couplings. In our case Λ are fixed by value of \( M_W \) (~ 80 GeV). As one can see the operators \( \mathcal{L}_0 \) and \( \mathcal{L}_c \) are \( \mathcal{C}, \mathcal{P}, \mathcal{CP} \)-invariant. \( \tilde{\mathcal{L}}_0 \) is the \( \mathcal{P} \) - and \( \mathcal{CP} \)-violating operator.

### 3 \( \mathcal{O}(\alpha) \) corrections to anomalous constants

Cross section of the \( WW \) pair production in the \( \gamma\gamma \) collisions to third order in \( \alpha \) is given by the sum of Born cross section, interference term between of Born and one-loop amplitudes, cross section of the \( WW\gamma \) production. We also include in consideration the process \( \gamma\gamma \rightarrow WWZ \) if energies exceed threshold of \( WWZ \) production:

\[ d\sigma(\gamma\gamma \rightarrow W^+W^-) = d\sigma^{\text{Born}}(\gamma\gamma \rightarrow W^+W^-) + \frac{1}{S} \text{Re}(M^{\text{Born}} M^{1-\text{loop}*}) d\Gamma^{(2)} + \]

\[ + d\sigma^{\text{soft}}(\gamma\gamma \rightarrow W^+W^-\gamma) + d\sigma^{\text{hard}}(\gamma\gamma \rightarrow W^+W^-\gamma) + d\sigma^{Z}(\gamma\gamma \rightarrow W^+W^-Z). \]

Real photon emission and one-loop correction are presented in figs.
Since one-loop and soft photon emission amplitudes are IR-divergent and only their sum is IR-finite it is convinient to consider soft and hard photon emissions separately [7]. $d\sigma^{soft}$ can be presented by factorizable expression [7]

$$d\sigma^{soft}(\gamma\gamma \rightarrow W^+W^-) = d\sigma^{Born}(\gamma\gamma \rightarrow W^+W^-)R^{soft},$$  

where

$$R^{soft} = \frac{2\alpha}{\pi} \left[ \left(-1 + \frac{1}{\beta} \left(1 - \frac{2M_W^2}{S}\right) \ln \left(\frac{1+\beta}{1-\beta}\right)\right) \ln(2\omega) + \frac{1}{n-4} - \ln(2\sqrt{\pi}) + \frac{1}{2} \ln \left(\frac{1+\beta}{1-\beta}\right) + \frac{1}{2\beta} \left(1 - \frac{2M_W^2}{S}\right) \left(Spence\left(-\frac{2\beta}{1-\beta}\right) - Spence\left(\frac{2\beta}{1+\beta}\right)\right) \right],$$

$\omega$ is soft photon energy cutoff, $\beta = \sqrt{1-4m_W^2/S}$, Spence – Spence function and $M_W$ is the mass of $W$ boson. The differential cross section of hard photon emission is given by equation:

$$d\sigma^{hard}(\gamma\gamma \rightarrow W^+W^-) = d\sigma(\gamma\gamma \rightarrow W^+W^-) - d\sigma^{soft}(\gamma\gamma \rightarrow W^+W^-).$$

One-loop amplitude $M^{1-loop}$ can be built due to usage of SCA (Algebra of Symbolic Calculations) programs ($MATHEMATICA$, $REDUCE$...) and transformations of scalar and tensor integrals to one-, two-, ..., six-point integrals. Cross section of $WWZ$ production on $\gamma\gamma$ beams are obtained through application of the Monte-Carlo method of numerical integration and exact covariant expressions of $\gamma\gamma \rightarrow W^+W^-Z$ amplitudes. Cross section as well as angular distributions of $WWZ$ production at $\gamma\gamma$ scattering are presented in our papers [7], [8].

Cross section of the process to third order in $\alpha$ can be written in the following form

$$\sigma(\gamma\gamma \rightarrow W^+W^-) = \sigma^B + R^{soft}\sigma^B + \sigma^{hard} + \sigma^Z.$$

Dependences of total cross section $\sigma(WW)$ on anomalous constant $a_0$ and $a_c$ with radiative correction are presented in figs. [9] [10]. We see that correction gives appreciable contributions to $\sigma(WW)$ (about $\sim 10\%$) only in the case of $a_c$ when the last one is rushing to the value of $0.05$. For $a_0$ and $\tilde{a}_0$ changes in anomalous part of $\sigma(WW)$ concerned with correction are negligible. So we conclude that in the first order of perturbation theory it has sense to include at considering of the anomalous Lagrangian $\mathcal{L}_c$ only. This fact is confirmed by contour plots presented in the paper (see figs. [5] [6]).

In order to evaluate the region of scattering angle where the radiative correction gives a considerable contribution we need to built graphs of angular distributions for $\delta\sigma$ in the $SM + \mathcal{L}_c$ model. Figure [7] shows this dependence.
Figure 3: Dependence of the cross section $\sigma(W^+W^-)$ on $a_0$. Solid line presents $\sigma^{\text{Born}}$, dashed line – cross section including radiative correction.

Taking into account the value of luminosity $L$ of photons about $100 fb^{-1}/\text{year}$, energy $\sqrt{S} \sim 1 TeV$ that corresponds to TESLA experimental conditions [6], we can build contour plots on $a_0$, $a_c$, $\tilde{a}_0$ of $\sigma(WW)$ with the lowest order radiative correction (see figs. 5, 6), where statistical error $\delta$ is equal to 0.05%. Calculation of $\delta \sigma$ leads to fact that the ellipse built on $(a_0, a_c)$ pair with $+2\delta$ error is shrunk by factor of $1/4$. This implies that inclusion of radiative correction in consideration increases confidence level what improves chances to discover deviations from SM at future experiments.

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Figure 4: Dependence of the cross section $\sigma(W^+W^-)$ on $a_c$. Solid line presents $\sigma^{Born}$, dashed line – cross section including radiative correction

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Figure 5: Contour plots on \((a_0, a_c)\) for \(+2\delta\) deviations of \(\sigma(W^+W^-)\)

Figure 6: Contour plots on \((a_c, \tilde{a}_0)\) for \(+2\delta\) deviations of \(\sigma(W^+W^-)\)

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Figure 7: Angular distributions of $\delta \sigma$ in $SM + \mathcal{L}_c$ model, where +(-) denotes right(left) circular polarization, 0 means longitudinal polarization and u – unpolarized case.