Anomalous quartic boson couplings via $\gamma\gamma \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow W^+W^-Z$ at the TESLA kinematics

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Abstract. The production of two and three electroweak gauge bosons in the high-energy $\gamma\gamma$ collisions gives the well opportunity to probe anomalous quartic gauge boson couplings. The influence of five possible anomalous couplings on the cross sections for $W^+W^-$, $W^+W^-\gamma$, $W^+W^-Z$ productions has been investigated at the TESLA kinematics ($\sqrt{s} \sim 1$ TeV). There are the reasonable discriminations between various anomalous contributions.
1. Introduction

The multiple vector-boson production will be a crucial test of the gauge structure of the Standard Model since the triple and quartic vector-boson couplings involved in this kind of reaction are constrained by the $SU(2) \otimes U(1)$ gauge invariance. The production of several vector bosons is the best place to search directly for any anomalous behavior of triple and quartic couplings.

Any small deviation from the Standard Model predictions for these couplings spoils the cancellations of the high energy behaviour between the various diagrams, giving rise to an anomalous growth of the cross section with energy [1]. It is important to measure the vector-boson selfcouplings and search deviations from the Standard Model (SM).

The trilinear and quartic gauge boson couplings affect different aspects of the electroweak interactions. The trilinear couplings directly test deviations from the non-Abelian structures of the SM [2]. On the contrary, the 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.

Thus there is the possibility that only the quartic couplings have values deviated from their SM values while the trilinear couplings don’t anomalous affect on the $W^+W^-$ and $W^+W^-Z$ ($W^+W^-\gamma$) productions [3]. 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.

Using the future high-energy linear $e^+e^-$-collider, one can obtain the colliding $\gamma e$ and $\gamma\gamma$ beams with almost the same energies as in $e^+e^-$-collisions and with high luminosity [1]. Processes $\gamma\gamma \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow W^+W^-Z$ at high energies will give unique possibility of quartic couplings investigation due to relatively large cross sections and low background for $WW$ and $WWZ$ productions. In this paper boson productions will be considered at energies $\sqrt{S}$ about 1 TeV corresponding to the TESLA kinematics.

In the following section we review the various types of anomalous quartic couplings that might be expected in extensions of the SM. In the section 3 the numerical results illustrating the effect of the anomalous couplings on the $WW$ and $WWZ$ cross sections as well as conclusions are presented.

2. Feynman rules for anomalous quartic gauge boson couplings

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 the lowest dimension of 6 [4, 5]. 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 we consider the 6-dimensional operators \[ \mathcal{L}_0 = -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \bar{W}^\alpha \tilde{W}_\alpha, \]

\[ \mathcal{L}_c = -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \bar{W}^\beta \tilde{W}_\alpha, \]

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

\[ \mathcal{L}_n = -\frac{e^2}{16\Lambda^2} a_n \epsilon_{ijk} F_{\mu\nu} W^i_{\mu\alpha} W^j_{\nu\alpha} W^k, \]

\[ \tilde{\mathcal{L}}_n = -\frac{e^2}{16\Lambda^2} \tilde{a}_n \epsilon_{ijk} \tilde{F}_{\mu\nu} W^i_{\mu\alpha} W^j_{\nu\alpha} W^k, \]

where we introduce the triplet of gauge bosons

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

and the field-strenght tensors

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

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

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

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

Now we can obtain Feynman rules for anomalous quartic gauge boson couplings.

\[ = \frac{e^2}{8\Lambda^2} \left( 4a_0 g^{\alpha\beta}(k_1 k_2) g_{\mu\nu} - k_1^\nu k_2^\mu + a_c ((k_1 k_2) g_{\mu\nu} + (k_1 k_2)(g^{\mu\alpha} g^{\nu\beta} + g^{\nu\alpha} g^{\mu\beta}) -

- k_1^\nu (k_2 g^{\mu\alpha} + k_2 g^{\mu\beta}) - k_2^\nu (k_1 g^{\nu\alpha} + k_1 g^{\nu\beta})) + 4\tilde{a}_0 g^{\alpha\beta} k_1\rho k_2\sigma \epsilon^{\mu\nu\rho\sigma} \right). \]
\[ \frac{e^2}{16\Lambda^2 \cos \theta_W} \left( a_n \left( -(k_1 k_2)(g^{\mu\alpha}g^{\nu\beta} - g^{\mu\beta}g^{\nu\alpha}) - (k_1 p_3)(g^{\mu\beta}g^{\nu\alpha} - g^{\mu\nu}g^{\alpha\beta}) \right) - (k_1 p_4)(g^{\mu\nu}g^{\alpha\beta} - g^{\mu\alpha}g^{\nu\beta}) + k_2(k_1 g^{\nu\beta} - k_1 g^{\nu\alpha}) + p_3(k_1 g^{\nu\alpha} - k_1 g^{\nu\alpha}) + p_4(k_1 g^{\beta\alpha} - k_1 g^{\beta\alpha}) - g^{\mu\nu}(k_1 p_3 - k_1 p_4) - g^{\mu\alpha}(k_1 p_3 - k_1 p_4) - g^{\mu\beta}(k_1 k_2 - k_1 k_2)) + \tilde{a}_n k_1 \epsilon_{\alpha\beta\mu\rho} + (k_1 + p_3)^{\alpha} \epsilon^{\beta\mu\rho} + (k_1 + p_4)^{\beta} \epsilon^{\nu\rho\mu} - (k_2 k_1)^{\sigma} g^{\nu\alpha} \epsilon^{\sigma\beta\mu\rho} - (p_3 - p_4)^{\sigma} g^{\beta\alpha} \epsilon^{\sigma\nu\mu\rho} - (p_4 - k_2)^{\sigma} g^{\nu\beta} \epsilon^{\sigma\alpha\mu\rho}. \]  

(5)

All momenta of bosons are supposed as incoming. Feynman diagrams for the \( \gamma\gamma \rightarrow W^+W^- \) and \( \gamma\gamma \rightarrow W^+W^-Z \) processes involving quartic gauge boson couplings are presented on Fig.1 and Fig.2.

![Feynman diagrams for W^+W^- production](image-url)
Anomalous quartic boson couplings via $\gamma\gamma \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow W^+W^-Z$ at the TESLA kinematics

Fig. 2. The first-order Feynman diagrams for $W^+W^-Z$-production

For the SM triple and quartic gauge boson couplings see for example [7].

3. Numerical Results

In this section we consider dependence of the cross sections for $\gamma\gamma \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow W^+W^-Z$ on the five anomalous couplings studied in the Section 2.

We start from explicit expression for the amplitude of the process $\gamma\gamma \rightarrow W^+W^-$

$$M = G_v \epsilon_\mu(k_1)\epsilon_\nu(k_2)\epsilon_\alpha(p_+)\epsilon_\beta(p_-) M_{T}^{\mu\nu\alpha\beta},$$

(6)

where

$$M_{T}^{\mu\nu\alpha\beta} = \sum_{i=1}^{3} M_{i}^{\mu\nu\alpha\beta},$$

(7)

$k_1, k_2, p_+, p_-$ are four-momenta for the $\gamma, \gamma, W^+, W^-$ and $\epsilon_\mu(k_1), \epsilon_\nu(k_2), \epsilon_\alpha(p_+), \epsilon_\beta(p_-)$ - polarizations, respectively.

$$G_v = e^3 \cot \theta_W.$$
It is convenient to define the triple-gauge-boson coupling as
\[ \Gamma_3^{\alpha\beta\gamma}(P_1, P_2) = [(2P_1 + P_2)^\beta g^{\alpha\gamma} - (2P_2 + P_1)^\alpha g^{\beta\gamma} + (P_2 - P_1)^\gamma g^{\alpha\beta}], \] (8)
the SM quartic-gauge-boson coupling as
\[ \Gamma_4^{\mu\nu\alpha\beta} = g^{\mu\alpha} g^{\nu\beta} + g^{\mu\beta} g^{\nu\alpha} - 2g^{\mu\nu} g^{\alpha\beta}, \] (9)
and the propagator tensor for the vector boson as
\[ D^{\mu\nu}(k) = \frac{(g_{\mu\nu} - k^\mu k^\nu/m^2)}{k^2 - m^2}. \] (10)

Anomalous quartic boson couplings are defined in (11) and (12). Using the expression defined above, the contributions of the three Feynman diagrams (see fig. 1) for the \( W W \)-production can be written as
\[ M_1^{\mu\nu\alpha\beta} = \Gamma_3^{\mu\alpha\xi}(-k_1, p_+) D_{\xi\lambda}(p_+ - k_1) \Gamma_3^{\nu\beta\lambda}(-k_2, p_-), \] (11)
\[ M_2^{\mu\nu\alpha\beta} = \Gamma_3^{\mu\beta\xi}(-k_1, p_-) D_{\xi\lambda}(p_- - k_1) \Gamma_3^{\nu\alpha\lambda}(-k_2, p_+), \] (12)
\[ M_3^{\mu\nu\alpha\beta} = \Gamma_4^{\mu\nu\alpha\beta}. \] (13)

The expressions of amplitude for a triple boson production (see fig. 2) can be defined in the following way:
\[ M_1^{\mu\nu\alpha\beta\gamma} = \Gamma_3^{\gamma\alpha\xi}(p_+, k_3) D_{\xi\sigma}(p_+ + k_3) \Gamma_3^{\mu\sigma\rho}(k_1, -(p_+ + k_3)) \] (14)
\[ D_{\rho\lambda}(p_+ - k_2) \Gamma_3^{\beta\mu\lambda}(-p_-, k_2) + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu] \]
\[ M_2^{\mu\nu\alpha\beta\gamma} = \Gamma_3^{\beta\xi}(k_3, p_-) D_{\xi\sigma}(p_- + k_3) \Gamma_3^{\gamma\sigma\rho}(-p_+, k_2) \] (15)
\[ D_{\rho\lambda}(k_1 - p_+) \Gamma_3^{\mu\alpha\lambda}(-p_+, k_1) + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu] \]
\[ M_3^{\mu\nu\alpha\beta\gamma} = \Gamma_3^{\mu\alpha\xi}(-k_2, p_-) D_{\xi\lambda}(k_2 - p_-) \Gamma_3^{\nu\beta\rho}(-k_3, k_1 - p_+)) \] (16)
\[ D_{\rho\lambda}(p_- - k_2) \Gamma_3^{\gamma\lambda\mu}(k_2, p_-) + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu] \]
\[ M_4^{\mu\nu\alpha\beta\gamma} = \Gamma_3^{\beta\rho\xi}(-p_-, k_2) D_{\xi\lambda}(k_2 - p_-) \Gamma_4^{\lambda\alpha\mu\gamma} + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu] \] (17)
\[ M_5^{\mu\nu\alpha\beta\gamma} = \Gamma_3^{\mu\alpha\xi}(k_1, -p_+) D_{\xi\lambda}(k_1 - p_+) \Gamma_4^{\nu\beta\alpha\gamma} + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu] \] (18)
\[ M_6^{\mu\nu\alpha\beta\gamma} = \Gamma_3^{\alpha\gamma\xi}(p_+, k_3) D_{\xi\lambda}(k_3 + p_+) \Gamma_4^{\lambda\beta\mu\nu} \] (19)
\[ M_7^{\mu\nu\alpha\beta\gamma} = \Gamma_3^{\gamma\beta\xi}(k_3, p_-) D_{\xi\lambda}(-k_3 - p_-) \Gamma_4^{\lambda\alpha\nu\mu} \] (20)
where [\( k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu \)] defines the crossed contributions of the initial photons. The covariant formulae of amplitudes for considering processes are also presented in (8) [7]. Using the
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Monte-Carlo method of integration \[9\] we obtain the cross section of $\gamma\gamma \rightarrow W^+W^-$ at various
Fig. 5. The effect of the anomalous $\tilde{a}_0$ coupling on the cross section $\sigma(W^+W^-)$, normalised to the SM values

Fig. 6. The comparison of the dependences of the cross sections $\sigma(W^+W^-)$. Solid line presents $a_0^-$, scratched line $a_c^-$, dotted line $\tilde{a}_0^-$-dependence

values of $\sqrt{S}$

$$\sigma = \sum_{\lambda_1\lambda_2\lambda_3\lambda_4} \int |M_{\lambda_1\lambda_2\lambda_3\lambda_4}|^2 d\Gamma,$$

(21)
Anomalous quartic boson couplings via $\gamma\gamma \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow W^+W^-Z$ at the TESLA kinematics

where $M_{\lambda_1\lambda_2\lambda_3\lambda_4}$ is the total amplitude of the process $\gamma\gamma \rightarrow W^+W^-$. $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ are polarizations of initial photons and final bosons respectively. The cross section $\sigma$ for $W^+W^-$ production at $\sqrt{S} = 1\text{TeV}$ is $\sim 110\text{pb}$ and for $W^+W^-Z$ production is $\sim 12\text{pb}$. We consider the following experimental conditions: unpolarized $\gamma\gamma$ beams at $\sqrt{S} = 1\text{ TeV}$ with luminosity $L = 100\text{fb}^{-1}/\text{year}$ according to TESLA TDR [10]. Note that $\sigma(W^+W^-)$ depends on $a_0$, $a_c$ and $\tilde{a}_0$, but $\sigma(W^+W^-Z)$ has additional dependence on $a_n$ and $\tilde{a}_n$. Figures 3 – 6 shows dependence of three total cross sections $\sigma(W^+W^-)$ on anomalous parameters. The cross section depends on anomalous couplings quadratically. The fact that the minima of the curves are close to the SM point $a_i = 0$ means that the interference between the anomalous and the standard part of the matrix element is very small. In the region for $a_i$ about 0.5 the anomalous part of the cross section achieves the values about $2\sigma_{SM} \sim 3\sigma_{SM}$. That stands for the evidence of great sensitivity of the cross section $\sigma(W^+W^-)$ to anomalous couplings. In figures 7 – 10 the dependences of the total cross sections $\sigma(W^+W^-)$ for $W^+W^-Z$ production are shown. Comparing two sets of figures on can conclude that the $W^+W^-Z$

![Fig. 7](image_url)  

Fig. 7. The effect of the anomalous $a_0$ coupling on the cross section $\sigma(W^+W^-Z)$, normalised to the SM values

production is more suitable (more sensitive) for analysing the anomalous $a_0$ coupling in case of unpolarized $\gamma\gamma$ collisions while $\gamma\gamma \rightarrow W^+W^-$ has greater abilities then previous process for investigation of $a_c$ and $\tilde{a}_0$. The last anomalous coupling $\tilde{a}_0$ aren’t examined by the investigation of $\gamma\gamma \rightarrow W^+W^-Z$ at all. The sensibilites of unpolarized $e^+e^- \rightarrow W^+W^-$ and $e^+e^- \rightarrow W^+W^-Z$ for considered anomalous couplings [11,12] is less in comparison with $\gamma\gamma$ beams by about ten times.

The influences $a_n$ and $\tilde{a}_n$ to $\sigma(W^+W^-Z)$ are shown in figures [13,14]. They are negligible in comparison with $a_0$, $a_c$. The couplings $a_n$ and $\tilde{a}_0$ almost have the same order.

The contour plots for different deviations from the SM $\gamma\gamma \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow W^+W^-Z$ total cross sections at $\sqrt{S} = 1\text{ TeV}$, when two of the five anomalous couplings are non-zero, are the most vivid and interesting for investigation of anomalous couplings. Figures [15,16]
Fig. 8. The effect of the anomalous $a_c$ coupling on the cross section $\sigma(W^+W^-Z)$, normalised to the SM values.

Fig. 9. The effect of the anomalous $\tilde{a}_0$ coupling on the cross section $\sigma(W^+W^-Z)$, normalised to the SM values.

presents contour plots for different pairs of $a_i$. Here $\sigma$ means a variance of total cross section.

We have investigated the sensitivity of $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to W^+W^-Z$ to genuine
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Fig. 10. Comparison of the dependences of the cross sections $\sigma(W^+W^-Z)$. Solid line presents $a_0^-$, scratched line - $a_c^-$, dotted line $\tilde{a}_0^-$dependence

Fig. 11. The effect of the anomalous $a_n$ coupling on the cross section $\sigma(W^+W^-Z)$, normalised to the SM values

anomalous quartic couplings: $a_0$, $a_c$, $\tilde{a}_0$, $a_n$, $\tilde{a}_n$ at the centre-of-mass energy $\sqrt{S} = 1\text{TeV}$. We have assumed that all other couplings obtained from 6-dimensional operators and trilinear couplings are equal to zero. If the last are non-zero [3] one would expect that limits obtained
It is necessary to note that the sensitivities of $W^+W^-$ and $W^+W^-Z$ productions in $\gamma\gamma$ collisions are large in comparison with these productions using $e^+e^-$ annihilation. It means
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that at high energies TESLA has the great chance to reveal "new physics" in the bosonic sector of the electroweak theory.
Fig. 16. Contour plots for $+2\sigma$, $+3\sigma$ deviations of $\sigma(W^+W^-Z)$ at $\int \mathcal{L} = 100 fb^{-1}$, $\sqrt{S} = 1 TeV$

Fig. 17. Contour plots for $+2\sigma$, $+3\sigma$ deviations of $\sigma(W^+W^-Z)$ at $\int \mathcal{L} = 100 fb^{-1}$, $\sqrt{S} = 1 TeV$

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Fig. 18. Contour plots for $+2\sigma$, $+3\sigma$ deviations of $\sigma(W^+W^-Z)$ at $\int \mathcal{L} = 100 fb^{-1}$, $\sqrt{S} = 1 TeV$

Fig. 19. Contour plots for $+2\sigma$, $+3\sigma$ deviations of $\sigma(W^+W^-Z)$ at $\int \mathcal{L} = 100 fb^{-1}$, $\sqrt{S} = 1 TeV$

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