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Anomalous quartic boson couplings via $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to W^+W^-Z$ 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 allows to check anomalous quartic gauge boson couplings. The influence of five possible anomalous couplings on the cross sections of W^+W^-, $W^+W^-\gamma$, W^+W^-Z productions has been investigated at the TESLA kinematics ($\sqrt{S} \sim 1$ TeV). There is the significant discrimination between various anomalous contributions.

1. Introduction

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

Any small deviation from the Standard Model predictions for these couplings reduces the cancellations of the various diagrams contributions at high energies, giving rise to an anomalous growth of the cross section with energy [1]. So it is important to estimate the vector-boson selfcouplings and measure deviations from the Standard Model (SM).

The triple and quartic gauge boson couplings affect different aspects of the electroweak interactions. The triple couplings directly test deviations from the non-Abelian structures of the SM [2]. On the contrary, the quartic gauge boson couplings lead to direct electroweak symmetry breaking, in particular in the scalar sector of the theory or, more generally, to "new physics" of electroweak gauge bosons.

In addition there is the possibility (for the purpose of simplification) that only quartic couplings have values deviated from their SM values while the triple couplings don't anomalously 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 interaction can explain and provide the first evidence of "new physics" in this sector of the electroweak theory.

At future high-energy linear e^+e^--colliders, one can obtain the colliding γe and $\gamma\gamma$ beams with almost the same energies as in e^+e^-- collisions and with high luminosity [1]. Processes $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to W^+W^-Z$ at high energies will give the 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 energy $\sqrt{S}$ about 1 TeV corresponding to the TESLA kinematics.

In the next section we review the various types of anomalous quartic couplings that might be expected beyond the SM. In the section 3 the numerical results and conclusions are presented illustrating the effect of the anomalous couplings on the WW and WWZ cross sections.

2. Feynman rules for anomalous quartic gauge boson couplings

In order to construct the structures contained anomalous quartic gauge boson couplings where at least one photon is involved one has to consider the operators with 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 closed to 1. Thus we consider the 6-dimensional operators [5]

$$
\begin{aligned}
\mathcal{L}_0 &= -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \bar{W}^\alpha \bar{W}_\alpha, \\
\mathcal{L}_c &= -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \bar{W}^\beta \bar{W}^\alpha, \\
\tilde{\mathcal{L}}_0 &= -\frac{e^2}{16\Lambda^2} \tilde{a}_0 F^{\mu\alpha} \tilde{F}_{\mu\beta} \bar{W}^\beta \bar{W}^\alpha, \\
\mathcal{L}_n &= -\frac{e^2}{16\Lambda^2} a_n \epsilon_{ijk} F^{\mu\nu} W^i_{\mu\alpha} W^j_\nu W^{\alpha,k}, \\
\tilde{\mathcal{L}}_n &= -\frac{e^2}{16\Lambda^2} \tilde{a}_n \epsilon_{ijk} \tilde{F}^{\mu\nu} W^i_{\mu\alpha} W^j_\nu W^{\alpha,k},
\end{aligned}
\tag{1}
$$

where we introduce the triplet of gauge bosons

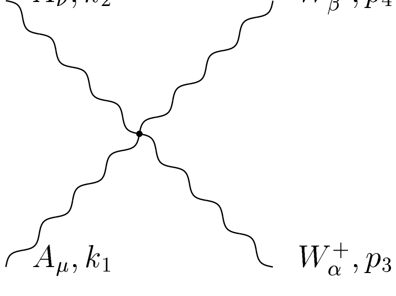
$$
\bar{W}_\mu = \left(\frac{1}{\sqrt{2}}(W^+_\mu + W^-_\mu), \frac{i}{\sqrt{2}}(W^+_\mu - W^-_\mu), \frac{1}{\cos\theta_W} Z_\mu \right) \tag{2}
$$

and the field-strength tensors

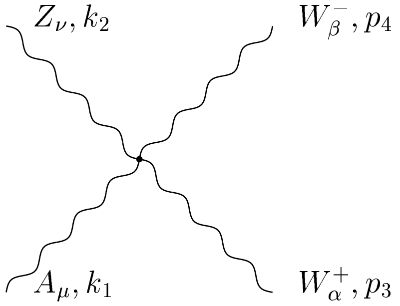
$$
\begin{aligned}
F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu, \\
W^i_{\mu\nu} &= \partial_\mu W^i_\nu - \partial_\nu W^i_\mu, \\
\tilde{F}_{\mu\nu} &= \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}.
\end{aligned}
\tag{3}
$$

The scale Λ is introduced to keep the coupling constant a_i dimensionless [6]. In practice Λ are specified in the frame of the chosen model for "new physics" supported anomalous quartic gauge boson couplings. In our calculations Λ are fixed by value of M_W (~ 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.

Equations (1) – (3) allow to obtain Feynman rules involving anomalous quartic gauge boson couplings.



$$
\begin{aligned}
&= \frac{e^2}{8\Lambda^2} \Big(4a_0 g^{\alpha\beta}((k_1k_2)g^{\mu\nu} - k_1^\nu k_2^\mu) + a_c((k_1^\alpha k_2^\beta + k_1^\beta k_2^\alpha)g^{\mu\nu} + (k_1k_2)(g^{\mu\alpha}g^{\nu\beta} + g^{\nu\alpha}g^{\mu\beta}) - \\
&\quad -k_1^\nu(k_2^\beta g^{\mu\alpha} + k_2^\alpha g^{\mu\beta}) - k_2^\nu(k_1^\beta g^{\mu\alpha} + k_1^\alpha g^{\mu\beta})) + 4\tilde{a}_0 g^{\alpha\beta} k_{1\rho} k_{2\sigma}\, \epsilon^{\mu\rho\nu\sigma} \Big) .
\end{aligned}
\tag{4}
$$



$$
\begin{aligned}
= \frac{e^2}{16\Lambda^2 \cos\theta_W} \big(a_n(&-(k_1k_2)(g^{\mu\alpha}g^{\nu\beta} - g^{\mu\beta}g^{\nu\alpha}) - (k_1p_3)(g^{\mu\beta}g^{\nu\alpha} - g^{\mu\nu}g^{\alpha\beta}) - \\
&-(k_1p_4)(g^{\mu\nu}g^{\alpha\beta} - g^{\mu\alpha}g^{\nu\beta}) + \\
&+k_2^\mu(k_1^\alpha g^{\nu\beta} - k_1^\beta g^{\nu\alpha}) + p_3^\mu(k_1^\beta g^{\nu\alpha} - k_1^\beta g^{\nu\alpha}) + p_4^\mu(k_1^\nu g^{\beta\alpha} - k_1^\alpha g^{\nu\beta}) - \\
&-g^{\mu\nu}(k_1^\beta p_3^\alpha - k_1^\alpha p_4^\beta) - g^{\mu\alpha}(k_1^\nu p_4^\beta - k_1^\beta k_2^\nu) - g^{\mu\beta}(k_1^\alpha k_2^\nu - k_1^\nu k_3^\alpha)) + \\
&\tilde{a}_n k_{1\rho}((k_1+k_2)^\nu \epsilon^{\alpha\beta\mu\rho} + (k_1+p_3)^\alpha \epsilon^{\beta\nu\mu\rho} + (k_1+p_4)^\beta \epsilon^{\nu\alpha\mu\rho} - \\
&-(k_2-k_1)_\sigma g^{\nu\alpha}\epsilon^{\sigma\beta\mu\rho} - (p_3-p_4)_\sigma g^{\beta\alpha}\epsilon^{\sigma\nu\mu\rho} - (p_4-k_2)_\sigma g^{\nu\beta}\epsilon^{\sigma\alpha\mu\rho}).
\end{aligned} \tag{5}
$$

All momenta of bosons are supposed to be coming into a boson vertex. Feynman diagrams for the $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to W^+W^-Z$ processes involving quartic gauge boson couplings are presented in fig.1 and fig.2 (in the case of $\gamma\gamma \to W^+W^-Z$ one needs in addition to consider the case of interchanged initial photons).

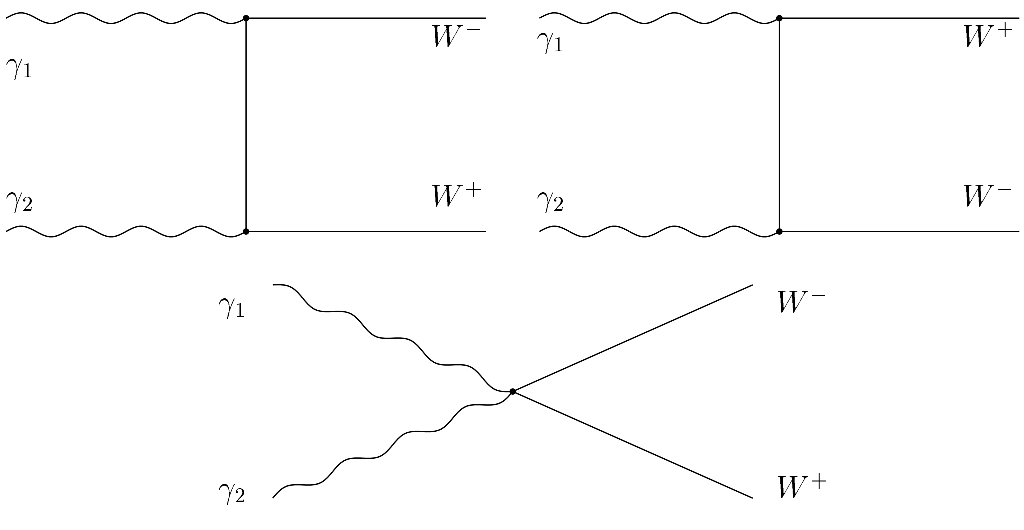


Fig. 1. The Feynman diagrams for W^+W^--production

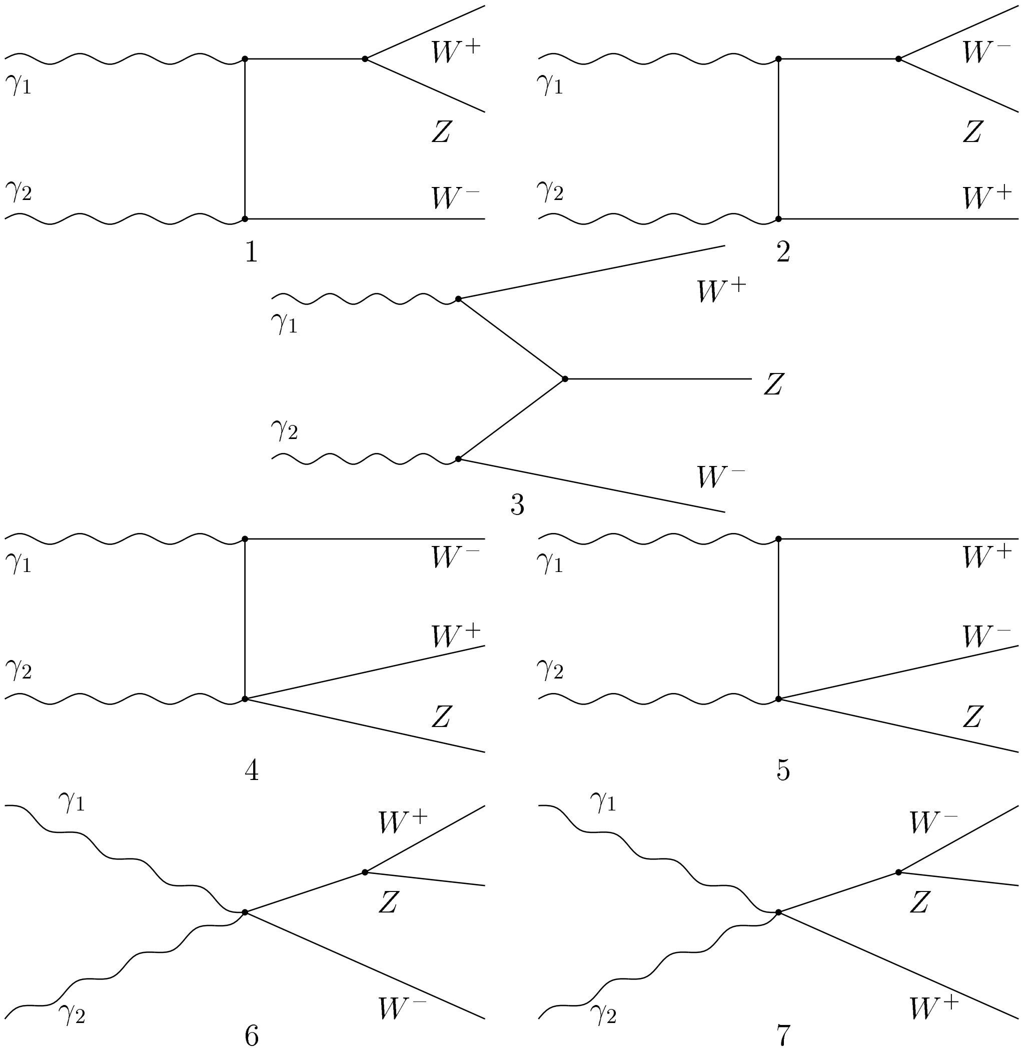


Fig. 2. The first-order Feynman diagrams for W^+W^-Z-production

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

3. Numerical Results

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

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

$$M = G_v \epsilon_\mu(k_1)\epsilon_\nu(k_2)\epsilon_\alpha(p_+)\epsilon_\beta(p_-)M_T^{\mu\nu\alpha\beta}, \tag{6}$$

where

$$M_T^{\mu\nu\alpha\beta} = \sum_{i=1}^{3} M_i^{\mu\nu\alpha\beta}, \tag{7}$$

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

$$G_v = e^3 \cot\theta_W.$$

It is convenient to define the SM triple-gauge-boson coupling as

$$\Gamma_3^{\alpha\beta\gamma}(P_1, P_2) =[(2P_1 + P_2)^\beta g^{\alpha\gamma} - (2P_2 + P_1)^\alpha g^{\beta\gamma} + (P_2 - P_1)^\gamma g^{\alpha\beta}], \tag{8}$$

the SM quartic-gauge-boson coupling as

$$\Gamma_4^{\mu\nu\alpha\beta} =g^{\mu\alpha}g^{\nu\beta} + g^{\mu\beta}g^{\nu\alpha} - 2g^{\mu\nu}g^{\alpha\beta}, \tag{9}$$

and the propagator tensor for the vector boson as

$$D^{\mu\nu}(k) =\frac{(g^{\mu\nu} - k^\mu k^\nu/m^2)}{k^2 - m^2}. \tag{10}$$

Anomalous quartic boson couplings are defined by eqs. (4) and (5). Using the expression presented above, the contributions of the three Feynman diagrams (see fig. 1) for the WW-production can be written in the following form

$$M_1^{\mu\nu\alpha\beta} =\Gamma_3^{\mu\alpha\xi}(-k_1, p_+)D_{\xi\lambda}(p_+ - k_1)\Gamma_3^{\nu\beta\lambda}(-k_2, p_-), \tag{11}$$

$$M_2^{\mu\nu\alpha\beta} =\Gamma_3^{\mu\beta\xi}(-k_1, p_-)D_{\xi\lambda}(p_- - k_1)\Gamma_3^{\nu\alpha\lambda}(-k_2, p_+), \tag{12}$$

$$M_3^{\mu\nu\alpha\beta} =\Gamma_4^{\mu\nu\alpha\beta}. \tag{13}$$

The expressions of amplitudes [7] for a triple boson production (see fig. 2) have the next form:

$$\begin{aligned} M_1^{\mu\nu\alpha\beta\gamma} =&\Gamma_3^{\alpha\gamma\xi}(p_+, k_3)D_{\xi\sigma}(p_+ + k_3)\Gamma_3^{\mu\sigma\rho}(k_1, -(p_+ + k_3)) \\ &D_{\rho\lambda}(p_- - k_2)\Gamma_3^{\beta\nu\lambda}(-p_-, k_2) + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu], \end{aligned} \tag{14}$$

$$\begin{aligned} M_2^{\mu\nu\alpha\beta\gamma} =&\Gamma_3^{\gamma\beta\xi}(k_3, p_-)D_{\xi\sigma}(p_- + k_3)\Gamma_3^{\sigma\nu\rho}(-(p_- + k_3), k_2) \\ &D_{\rho\lambda}(k_1 - p_+)\Gamma_3^{\alpha\mu\lambda}(-p_+, k_1) + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu], \end{aligned} \tag{15}$$

$$\begin{aligned} M_3^{\mu\nu\alpha\beta\gamma} =&\Gamma_3^{\mu\alpha\xi}(k_1, -p_+)D_{\xi\sigma}(k_1 - p_+)\Gamma_3^{\gamma\sigma\rho}(-k_3, (k_1 - p_+)) \\ &D_{\rho\lambda}(p_- - k_2)\Gamma_3^{\nu\beta\lambda}(-k_2, p_-) + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu], \end{aligned} \tag{16}$$

$$M_4^{\mu\nu\alpha\beta\gamma} =\Gamma_3^{\beta\nu\xi}(-p_-, k_2)D_{\xi\lambda}(k_2 - p_-)\Gamma_4^{\lambda\alpha\mu\gamma} + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu], \tag{17}$$

$$M_5^{\mu\nu\alpha\beta\gamma} =\Gamma_3^{\mu\alpha\xi}(k_1, -p_+)D_{\xi\lambda}(k_1 - p_+)\Gamma_4^{\lambda\beta\nu\gamma} + [k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu], \tag{18}$$

$$M_6^{\mu\nu\alpha\beta\gamma} =\Gamma_3^{\alpha\gamma\xi}(p_+, k_3)D_{\xi\lambda}(k_3 + p_+)\Gamma_4^{\lambda\beta\nu\mu}, \tag{19}$$

$$M_7^{\mu\nu\alpha\beta\gamma} =\Gamma_3^{\gamma\beta\xi}(k_3, p_-)D_{\xi\lambda}(-k_3 - p_-)\Gamma_4^{\lambda\alpha\nu\mu}, \tag{20}$$

where $[k_1 \leftrightarrow k_2; \mu \leftrightarrow \nu]$ denotes the crossed contributions of the initial photons. Through

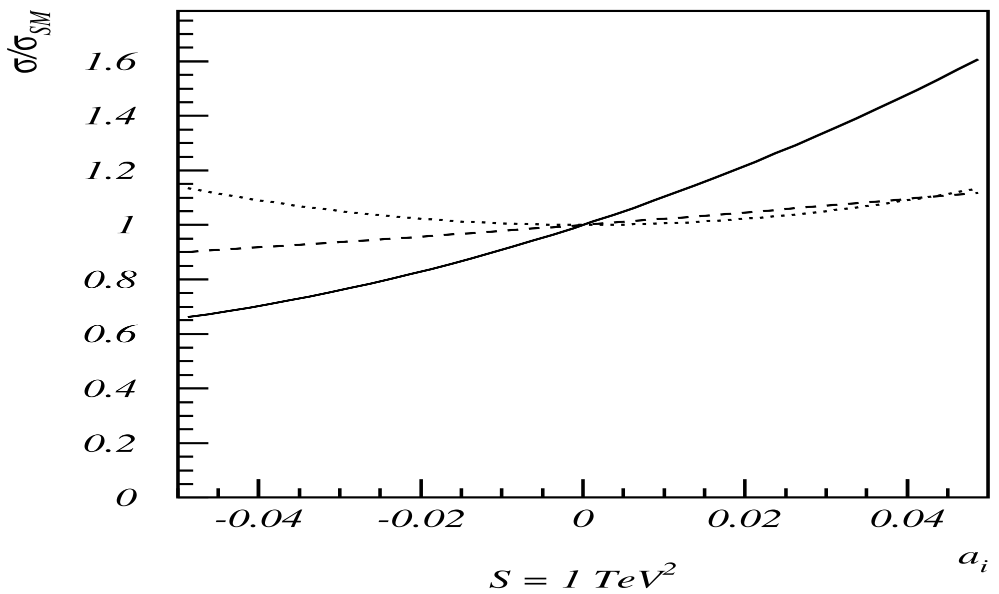


Fig. 3. The comparison of the dependencies of the cross sections $\sigma(W^+W^-)$ Solid line presents a_0-, dashed line – a_c-, dotted line – $\tilde{a}_0$-dependence

the Monte-Carlo method of integration [8] we obtain the cross section of $\gamma\gamma \to W^+W^-$ at various values of $\sqrt{S}$

$$\sigma = \sum_{\lambda_1\lambda_2\lambda_3\lambda_4} \frac{1}{2S} \int |M_{\lambda_1\lambda_2\lambda_3\lambda_4}|^2 d\Gamma, \tag{21}$$

where $M_{\lambda_1\lambda_2\lambda_3\lambda_4}$ is the total amplitude of the process $\gamma\gamma \to W^+W^-$. $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ are the polarizations of initial photons and final bosons respectively. The cross section σ of W^+W^- production at $\sqrt{S} = 1\text{TeV}$ amounts $110pb$ but in case of $\gamma\gamma \to W^+W^-Z$ it is equal to $12pb$. We assume existence of the following experimental conditions: unpolarized $\gamma\gamma$ beams at $\sqrt{S} = 1$ TeV with luminosity $\mathcal{L} = 100fb^{-1}/year$ according to TESLA TDR [9]. 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 $\tilde{a}_n$. Figure 3 demonstrates the dependencies of three total cross sections $\sigma(W^+W^-)$ on anomalous parameters. The fact that the curves' minima are closed to the SM point $a_i = 0$ means very small interference between the anomalous and the standard part of the matrix element. The anomalous part of the cross section ranges from $0.6\sigma_{SM}$ to $-0.35\sigma_{SM}$ in a_0's interval from 0.05 to -0.05, in cases of a_c and $\tilde{a}_0$ the values of anomalous cross section are significantly smaller. It stands for great sensitivity of the $\sigma(W^+W^-)$ cross section to a_0 anomalous coupling. In the figure 4 the dependencies of the total cross sections $\sigma(W^+W^-Z)$ for W^+W^-Z production are shown. Comparing two sets of figures one can conclude that the triple boson production weakly depends on the anomalous couplings at all.

Processes of e^+e^- annihilation with multiple boson production: $W^+W^-\gamma$, $ZZ\gamma$, $Z\gamma\gamma$ could be an another instrument beside $\gamma\gamma$ scattering to probe anomalous quartic boson interaction. Undoubtedly it would be interesting to compare results obtained from e^+e^- annihilation and $\gamma\gamma$ scattering, and then to choose one process over another in some kinematic region provided by an experiment. In ref. [6] graphs of σ/σ_{SM} ratio and contour plots for different

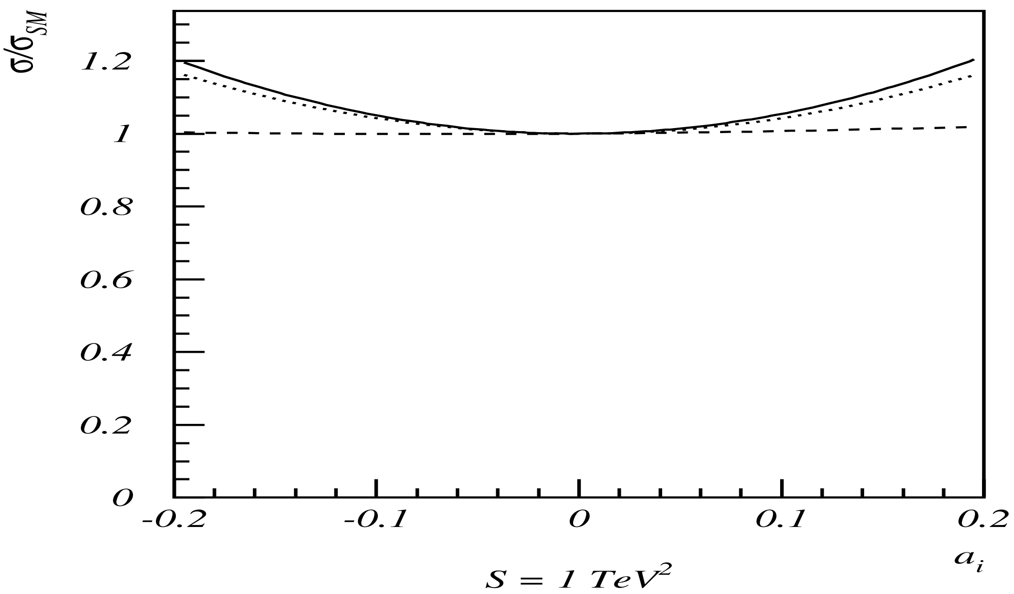


Fig. 4. Comparison of the dependencies of the cross sections $\sigma(W^+W^-Z)$ Solid line presents a_0-, dashed line – a_c-, dotted line – $\tilde{a}_0$-dependence

pair of anomalous couplings in $e^+e^- \to W^+W^-\gamma, ZZ\gamma, Z\gamma\gamma$ processes were plotted. One can conclude that in experiments of probing anomalous quartic boson interaction at high energies one should prefer rather $\gamma\gamma \to W^+W^-, W^+W^-Z$ than $e^+e^- \to W^+W^-\gamma, ZZ\gamma, Z\gamma\gamma$. Because anomalous contribution to cross sections of $\gamma\gamma$ scattering is larger than in the case of e^+e^- collisions at the same restrictions on anomalous constants.

The influences a_n and $\tilde{a}_n$ to $\sigma(W^+W^-Z)$ are shown in figures 5 – 6. They are negligible in comparison with a_0, a_c. The couplings a_n and $\tilde{a}_0$ have almost the same order.

The contour plots for different deviations from the SM of $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to W^+W^-Z$ total cross sections at $\sqrt{S} = 1$ TeV, when two of the five anomalous couplings are non-zero, are the most interesting for investigation of anomalous couplings. Figures 7 – 14 presents contour plots for different pairs of a_i. Here δ means a statistical error of total cross section. Statistical error δ of boson pair production amounts 0.3% and it comes to 2% in $\gamma\gamma \to W^+W^-Z$ process.

We have investigated the sensitivity of $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to W^+W^-Z$ to genuine anomalous quartic couplings: a_0, a_c, $\tilde{a}_0$, a_n, $\tilde{a}_n$ at the centre-of-mass energy $\sqrt{S} = 1$TeV. We have assumed that all other couplings obtained from 6-dimensional operators and triple couplings are equal to zero. If the last one are non-zero [3] one would expect that limits obtained on the quartic couplings can been affected.

Note that the sensitivities of W^+W^- and W^+W^-Z productions to the anomalous constants in $\gamma\gamma$ collisions are large in comparison with multiple boson productions in e^+e^- annihilation. It means that at high energies TESLA has the great chance to reveal "new physics" in the bosonic sector of the electroweak theory.

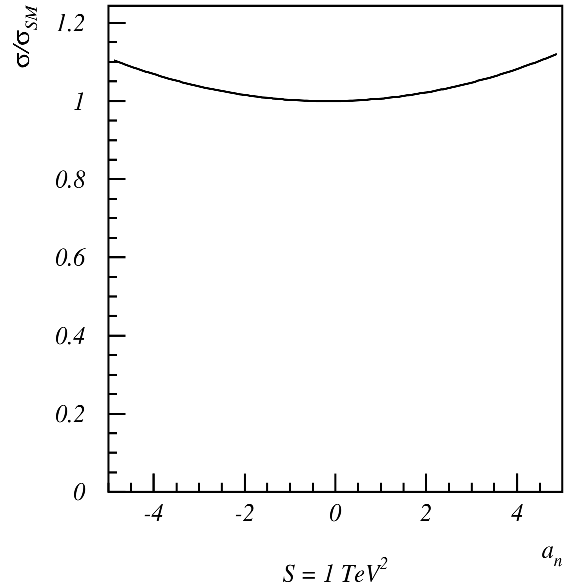


Fig. 5. Anomalous effect from a_n coupling on the cross section $\sigma(W^+W^-Z)$ normalized to the SM values

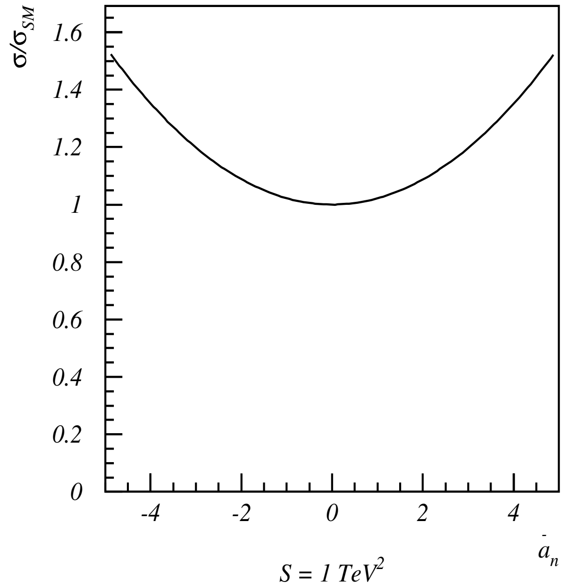


Fig. 6. Anomalous effect from $\tilde{a}_n$ coupling on the cross section $\sigma(W^+W^-Z)$ normalized to the SM values

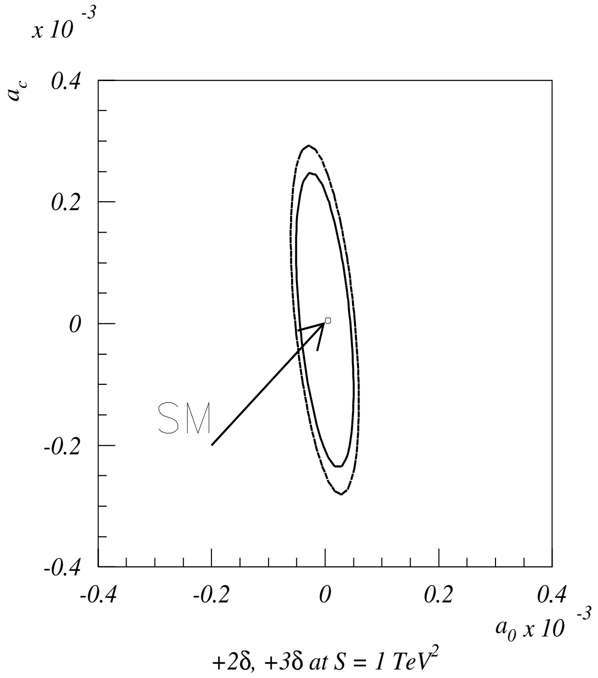


Fig. 7. Contour plots on $(a_0,\ a_c)$ for $+2\delta$, $+3\delta$ deviations of $\sigma(W^+W^-)$

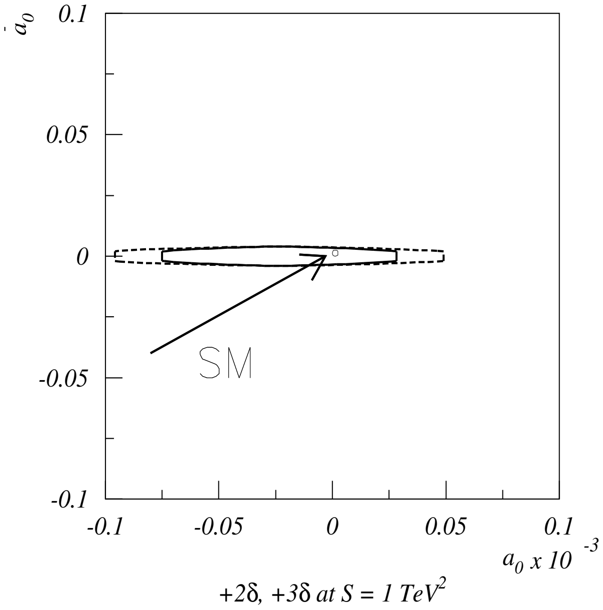


Fig. 8. Contour plots on $(a_0,\ \tilde{a}_0)$ for $+2\delta$, $+3\delta$ deviations of $\sigma(W^+W^-)$

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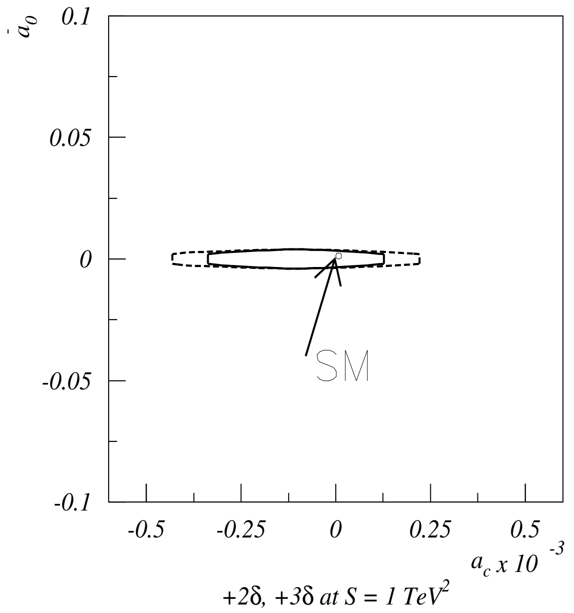

Fig. 9. Contour plots on $(a_c,\tilde{a}_0)$ for $+2\delta$, $+3\delta$ deviations of $\sigma(W^+W^-)$

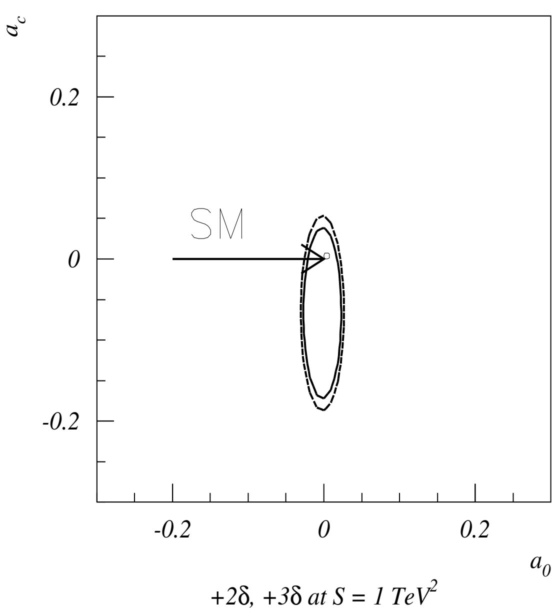

Fig. 10. Contour plots on $(a_0,\, a_c)$ for $+2\delta$, $+3\delta$ deviations of $\sigma(W^+W^-Z)$

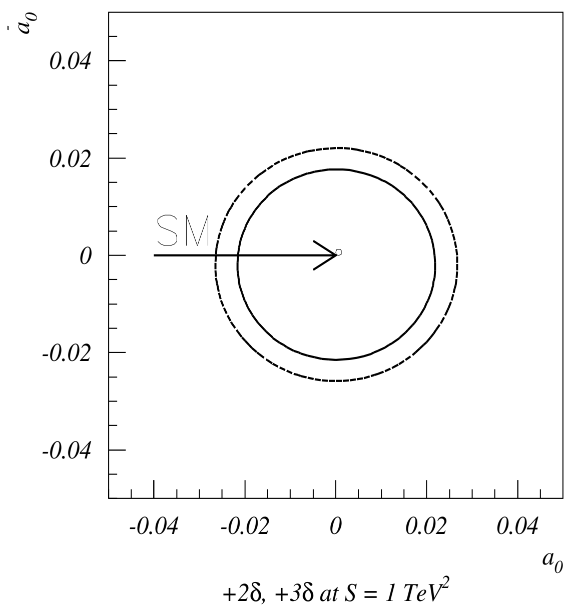

Fig. 11. Contour plots on $(a_0,\, \tilde{a}_0)$ for $+2\delta$, $+3\delta$ deviations of $\sigma(W^+W^-Z)$

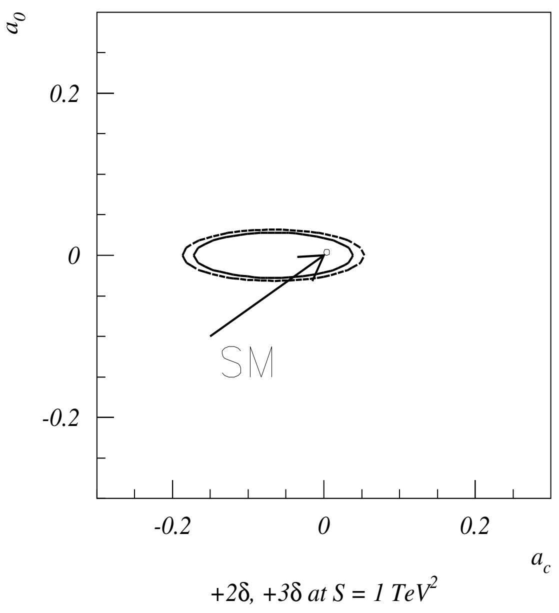

Fig. 12. Contour plots on $(a_c,\tilde{a}_0)$ for $+2\delta$, $+3\delta$ deviations of $\sigma(W^+W^-Z)$

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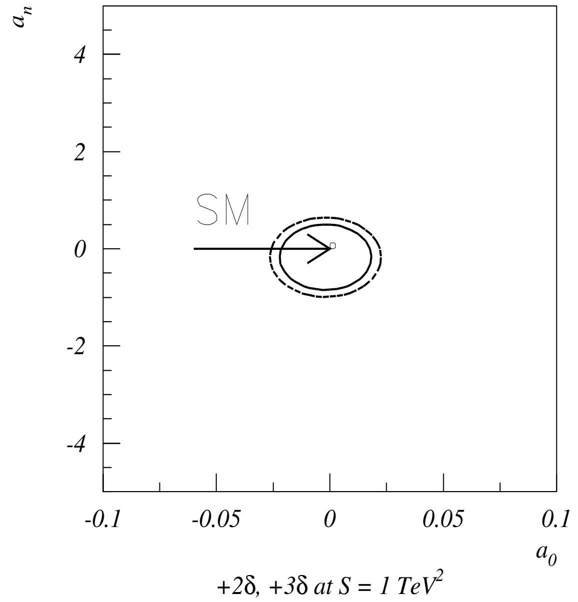

Fig. 13. Contour plots on (a_0, a_n) for $+2\delta$, $+3\delta$ deviations of $\sigma(W^+W^-Z)$

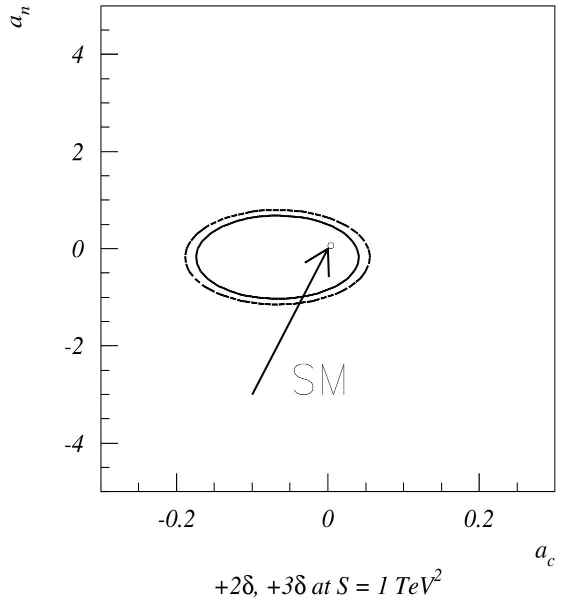

Fig. 14. Contour plots on (a_0, $\tilde{a}_n$) for $+2\delta$, $+3\delta$ deviations of $\sigma(W^+W^-Z)$

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