BSM contributions to the $Z\gamma\gamma$ and $ZZ\gamma$ self couplings at high energies

N L Belyaev, A H Kamaletdinov and E Y Soldatov

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

E-mail: NLBelyayev@mephi.ru, Kamaletdinov.A.H@yandex.ru, EYSoldatov@mephi.ru

Abstract. The CP conserving $Z\gamma\gamma$ and $ZZ\gamma$ couplings in the SM and MSSM models at loop level were investigated. For the both models, the coupling parameters $h_Z$, $h_{\gamma}$, $f_{\gamma}$ were estimated for the energy ranges, accessible at the LHC. Extension of the considered energy range up to 14 TeV leads to a possibility to constrain theories by using experimental limits on anomalous couplings from the LHC experiments. It was found that in order to constrain the parameters of the MSSM model, a measurement accuracy of the order of $10^{-7}$ is required.

1. Introduction

The searches for deviations from the Standard Model (SM) become more and more popular nowadays. The main target of such activities is to find the right directions for SM extension. The ultimate goal is to construct more general theory, which can explain e.g. non-zero neutrino mass and possibly incorporate the gravity into one common theory.

The direct searches of the effects beyond the Standard Model (BSM) at the LHC experiments show almost nothing [1,2]. Since the increase of collisions energy is not planned in the near future, the situation is not expected to change.

On the other hand, the indirect searches of the BSM physics should become more sensitive, since they benefit from the growing integrated luminosity. The measurements of rare SM processes provide good opportunity to test the possible deviations from the SM. The multiboson production is one of the best tools to test the SM [3]. Some couplings such as $Z\gamma\gamma$ and $ZZ\gamma$ are absent in the SM at tree level. However, BSM effects can lead to their appearance [4]. The searches of such anomalous couplings are being carried out by leading experimental collaborations such as ATLAS [5,6], CMS [7] and others. Besides these leading-order effects, one can expect loop-order contributions to these couplings. These loop-order effects are expected from both the SM and BSM theories.

In case of significant deviations from the SM are not found, the experimental constraints on the anomalous couplings can reach an accuracy of loop-order effects. In this case it will be possible to directly measure the coupling parameters from the corresponding loop contributions. It should be noted that different theories predict different loop contributions to the coupling parameters.

In this paper, the predictions of one-loop contributions to the couplings $h_Z^2$, $h_Z$ and $f_{\gamma}$ are reported for the SM and MSSM models in case of $pp$ collisions with up to $\sqrt{s} = 14$ TeV.
2. Loop contribution to the $Z\gamma\gamma$ and $ZZ\gamma$ couplings

First of all, the results obtained in the work [8] were reproduced and extended in order to put constraints on the CP-conserving neutral couplings $h_3^\gamma$, $h_3^Z$ and $f_5^\gamma$ in the $\gamma \rightarrow Z\gamma$, $Z \rightarrow Z\gamma$ and $\gamma \rightarrow ZZ$ decays, respectively, up to $\sqrt{s} = 14$ TeV for the SM and MSSM models.

The $h_3^\gamma$, $h_3^Z$ and $f_5^\gamma$ couplings were considered in the $\gamma \rightarrow Z\gamma$, $Z \rightarrow Z\gamma$ and $\gamma \rightarrow ZZ$ decays, respectively, up to $\sqrt{s} = 14$ TeV for the SM and MSSM models because they can make a significant contribution to the decay width which could in this case become noticeable in the experiment.

![Fermionic triangle loop diagram](image)

Figure 1. Fermionic triangle loop diagram.

The corresponding decay amplitudes can be written as follows [8]:

$$
\Gamma^{\alpha\beta\mu}_{Z\gamma V} = \frac{i(s - m_V^2)}{m_Z^2} \left( h_V^\gamma (q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + h_V^Z \frac{m_Z^2}{m_V^2} (P_\alpha (P q_2) g^{\mu\beta} - q_2^\mu P^{\beta}) - h_3^V \epsilon^{\alpha\beta\rho\sigma} q_2^\rho - h_4^V \frac{m_Z^2}{m_V^2} P^{\alpha\beta\rho\sigma} P_\sigma q_2^\rho \right)$$

(1)

$$
\Gamma^{\alpha\beta\mu}_{ZZ V} = \frac{i(s - m_Z^2)}{m_Z^2} \left( f_V^\gamma (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) - f_5^V \epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho \right)
$$

(2)

The results obtained in the work [8] were improved and the possibility to constrain the MSSM parameters by using observational data, obtained by the LHC experiments, was investigated [5, 9]. The effective couplings $h_V^\gamma$, and $f_V^\gamma$ here defined as the coefficients of the terms $\epsilon^{\mu\alpha\beta\rho} q_2^\rho$ and $\epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho$, respectively, and are described by the equation [3]

$$
\begin{align*}
    h_3^\gamma (j) &= -N_f \frac{e^2 Q_j^2 g_{aj}}{2\pi^2 \sin \Theta_w \cos \Theta_w} I^3_3; \\
    h_3^Z (j) &= -N_f \frac{e^2 Q_j^2 g_{aj}}{4\pi^2 \sin^2 \Theta_w \cos^2 \Theta_w} I^2_3; \\
    f_5^\gamma (j) &= N_f \frac{e^2 Q_j^2 g_{aj}}{4\pi^2 \sin^2 \Theta_w \cos^2 \Theta_w} I^3_3.
\end{align*}
$$

(3)

The expressions for $I^3_3$, $I^2_3$, $I^3_3$ in equation (3) can be taken from [8]; $g_{aj} \equiv I_{3,j}$ is the third isospin projection of considering j-th particle and $g_{aj} \equiv I_{3,j}(1 - 4 |Q_j| \sin \Theta_w)$. 


Figure 2. The SM and MSSM contributions to the $h_3^\gamma$ (a), $h_3^Z$ (b) and $f_5^\gamma$ (c) couplings as functions of $\sqrt{s}$; $h_3^\gamma$ (d), $h_3^Z$ (e) and $f_5^\gamma$ (f) couplings as functions of $\Lambda$. 
The allowed regions of the effective couplings $h^\gamma_3$, $h^Z_3$ and $f^\gamma_5$, extracted from the experiments at the moment, are shown in table 1.

In order to calculate the loop amplitudes the approach suggested in [8] was used. All calculations were performed using the Passarino and Veltman reduction procedure [10]. The idea is to reduce the one-loop integrals to a linear combination of the Passarino and Veltman functions.

Obtained results for SM and MSSM models are shown in figure 2, where on the (a,b,c) plots shown the values of the couplings $h^\gamma_3$, $h^Z_3$ and $f^\gamma_5$ respectively as functions of $\sqrt{s}$, whereas (c,d,e) plots represent the absolute values of such couplings as functions of $\Lambda$. Here $\Lambda$ is a free parameter of the MSSM model (characteristic energy scale of the MSSM). The predicted absolute values of $h^\gamma_3$, $h^Z_3$ and $f^\gamma_5$ couplings for SM and MSSM ($\Lambda=150$ GeV) models are presented in tables 2 and 3 respectively.

**Table 1.** Experimental constrains on the effective couplings $h^\gamma_3$, $h^Z_3$ and $f^\gamma_5$ [5,9].

| $\sqrt{s}$, TeV | $h^\gamma_3$ | $h^Z_3$ | $f^\gamma_5$ |
|-----------------|--------------|----------|--------------|
| 7               | $[-2.9 \div 2.9] \cdot 10^{-3}$ | $[-2.7 \div 2.7] \cdot 10^{-3}$ | $[-1.6 \div 1.5] \cdot 10^{-2}$ |
| 8               | $[-9.5 \div 9.9] \cdot 10^{-4}$ | $[-7.8 \div 8.6] \cdot 10^{-4}$ | $[-3.8 \div 3.8] \cdot 10^{-3}$ |
| 13              | $[-3.7 \div 3.7] \cdot 10^{-4}$ | $[-3.2 \div 3.3] \cdot 10^{-4}$ | $[-6.8 \div 7.5] \cdot 10^{-4}$ |

**Table 2.** Absolute values of the effective couplings for the SM.

| $\sqrt{s}$, TeV | $h^\gamma_3 \cdot 10^8$ | $h^Z_3 \cdot 10^8$ | $f^\gamma_5 \cdot 10^8$ |
|-----------------|-------------------------|-------------------|-------------------------|
| 7               | 2.59                    | 0.95              | 0.95                    |
| 8               | 1.62                    | 0.59              | 0.59                    |
| 13              | 0.29                    | 0.10              | 0.11                    |
| 14              | 0.22                    | 0.08              | 0.08                    |

**Table 3.** Absolute values of the effective couplings for the SM + Chargino.

| $\sqrt{s}$, TeV | $h^\gamma_3 \cdot 10^8$ | $h^Z_3 \cdot 10^8$ | $f^\gamma_5 \cdot 10^8$ |
|-----------------|-------------------------|-------------------|-------------------------|
| 7               | 2.16                    | 9.53              | 0.90                    |
| 8               | 1.34                    | 7.16              | 0.62                    |
| 13              | 0.23                    | 2.58              | 0.18                    |
| 14              | 0.18                    | 2.22              | 0.14                    |

3. Conclusion / Discussion

The predictions proposed in paper [8] were extended up to 14 TeV in order to compare them with the existing and future constraints from the LHC experiments. The proposed approach allows to set the constraints on free parameters of the BSM models. Predictions made in this paper are directly applicable to the searches for anomalous couplings, which are being carried out by the LHC experiments. In case of SM and MSSM the expected values for coupling parameters of the order of $10^{-8} \div 10^{-7}$ will be likely accessible on HL-LHC. The considered approach demonstrates great potential and can be used to constrain other BSM theories.
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References
[1] URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2020-011/
[2] URL: https://cds.cern.ch/record/2204922
[3] Soldatov E Y 2019 EPJ Web Conf. 222 01002
[4] Baur U and Berger E 1993 Phys. Rev. D 47 4889
[5] Aad G et al. (ATLAS collaboration) 2018 J. High Energy Phys. 12 010
[6] Aad G et al. (ATLAS collaboration) 2020 J. High Energy Phys. 03 054
[7] Aarnio A O et al. (CMS Collaboration) 2018 Preprint CMS-PAS-SMP-16-004 URL: https://cds.cern.ch/record/2204922
[8] Gounaris G J, Layssac J and Renard F M 2000 Phys. Rev. D 62 073013
[9] Aarnio A O et al. (CMS Collaboration) 2020 Subm to EPJ C
[10] Ellis K R, Kunszt Z, Melnikov K and Zanderighi G 2012 Phys. Rept. 518 141–250