Study of the LHC experiments sensitivity to anomalous quartic gauge couplings in $Z\gamma\gamma$ production during Run2

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Abstract. Run2 sensitivity to anomalous quartic gauge couplings was estimated for ATLAS experiment at LHC with increased energy of proton-proton collisions $\sqrt{s} = 13$ TeV and expected 40 fb^{-1} of integral luminosity. Simulation of $Z\gamma\gamma$ process with anomalous $ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$ couplings was performed using VBFNLO MC generator. Differential distributions on four-body invariant mass of final state particles was used for extraction of expected limits on Effective Field Theory parameters $f_{T0}/\Lambda^4, f_{T5}/\Lambda^4, f_{T9}/\Lambda^4, f_{M2}/\Lambda^4, f_{M3}/\Lambda^4$. Combined limits are obtained from two charged leptonic decay channels of Z boson ($Z\gamma\gamma \to l^+l^-\gamma\gamma$, where $l = e$ or μ). Unitarity of expected limits was studied using dipole form factor approach.

1. Introduction

Run2 at Large Hadron Collider will give an opportunity to study the forefront of high energy physics. Therefore in this paper we are interested to probe the precision of Standard Model (SM) predictions at Run2 energy scale and at the same time to put the constraints on effects of the "new physics" (NP) beyond the SM. Indirect search of NP aiming to observe its low-energy signatures is an effective method for exploring NP, which is not reachable at current experimental energies. The model independent approach of Effective Field Theory [1, 2] is able to parametrize any kind of NP via anomalous gauge bosons couplings in effective Lagrangian:

$$\mathcal{L}_{eff} = \sum_n \frac{1}{\Lambda^n} \sum_i f_i^{(n+4)} O_i^{(n+4)}, \tag{1}$$

where $\Lambda \gg \sqrt{\hat{s}}$ is the effective energy scale of the theory and $O_i^{(n+4)}$ are operators describing the couplings together with corresponding parameters $f_i^{(n+4)}/\Lambda^n$. $Z\gamma\gamma$ production apart from initial- and final-state radiation can be realized through anomalous quartic gauge couplings (aQGCs) $ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$. AQGCs are parametrized via 19 $O_i^{(8)}$ operators of [TeV^8] dimension. Among parameters corresponding to them we have chosen to set the expected limits on $f_{T0}/\Lambda^4, f_{T5}/\Lambda^4, f_{T9}/\Lambda^4, f_{M2}/\Lambda^4, f_{M3}/\Lambda^4$. The choice of these parameters is motivated by the facts, that only M- and T-type operators give a contribution in couplings under study [3] and it is possible to compare limits on them with previous results. f_{T9}/Λ^4 is a most of interest, since it can be measured only in processes with neutral currents and therefore $Z\gamma\gamma$ production

has strong sensitivity to this parameter. f_{T0}/Λ^4 is also in favor because of its contribution in numerous aQGCs, that is why it is studied in wide range of vector boson fusion and scattering processes.
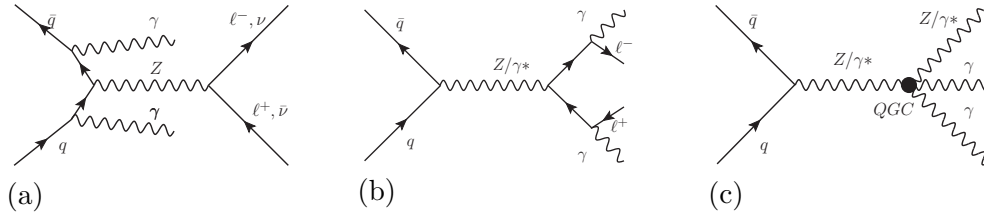

Figure 1. Feynman diagrams of $Z\gamma\gamma$ process: (a) initial-state radiation, (b) final-state radiation, (c) anomalous quartic gauge boson couplings $Z\gamma\gamma\gamma/ZZ\gamma\gamma$. [4]

2. $Z\gamma\gamma$ signal and background modeling

Signal and background simulation is performed for 40 fb^{-1} data of proton-proton collisions with $\sqrt{s} = 13$ TeV using ATLAS experiment geometry. Cross section of exclusive ($N_{jets} = 0$) SM and aQGC $Z\gamma\gamma$ process is calculated with `VBFNLO` [5, 6, 7] matrix element generator at the next-to-leading order. Main background comes from $Z\gamma$ inclusive production [4] with further misidentification of hadron jet as a photon. $Z\gamma + jet$ is simulated via `MadGraph` [8] MC generator and `Pythia-PGS` package [9] at leading order and jet-to-photon fake rate [10] is applied to resulting number of events. Electron (e^+e^-) and muon ($\mu^+\mu^-$) channels of Z boson decay are considered. Object and event selections are identical to recent 8 TeV ATLAS $Z\gamma\gamma$ analysis [4].

3. Expected limits calculation and phase space optimization

One-dimentional expected limits on aQGC were extracted using frequentist profile likelihood ratio method, which is performed via large number of pseudo-experiments. Confidential interval of their values corresponds to 95% confidence level. Second order polynomial parameterization of expected signal on aQGC parameters is necessary for limits calculation. It is obtained from `VBFNLO` cross-section the following parametrization

$$\sigma = p_0 + p_1\left(f_i/\Lambda^4\right) + p_2\left(f_i/\Lambda^4\right)^2, \tag{2}$$

taking into account an integrated luminosity (40 fb^{-1}), efficiencies of reconstruction (C), acceptance (A) and transition from parton to particle level (C^*). Efficiencies and their systematic uncertainties are taken from the 8 TeV ATLAS $Z\gamma\gamma$ analysis [4] under assumption that they are weakly dependent on energy of collision. A number of estimated background events is also required for limits calculation.

To improve the expected limits an additional selection on $m(l^+l^-\gamma\gamma)$ mass is used. Differential distribution on this variable for SM and aQGC signal and also for estimated background is presented in figure 2. It could be seen, that aQGC enhances the high-energy tail of the distribution, therefore $m(l^+l^-\gamma\gamma)$ distribution is the most sensitive to aQGC presence, since this variable corresponds to $\sqrt{\hat{s}}$ of $Z\gamma\gamma$. Dependences of expected limits on $m(l^+l^-\gamma\gamma)$ threshold are studied in order to reduce background and to set the most stringent limits. Favored parameters f_{T0}/Λ^4 and f_{T9}/Λ^4 are considered to have common threshold, where they both take the minimal values. Resulting limits with and without chosen threshold of 960 GeV are shown in Table 1.
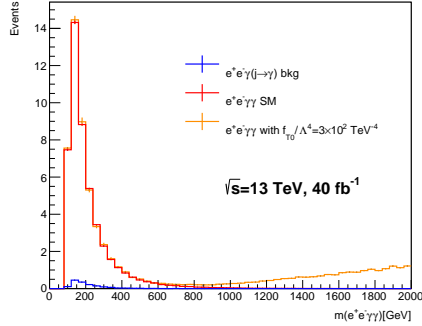
Figure 2. Differential distributions on triboson $Z\gamma\gamma$ mass for SM, with non-zero f_{T0}/Λ^4 parameter and for $Z\gamma(j \to \gamma)$ background.

Table 1. Expected limits on f_{T0}/Λ^4, f_{T5}/Λ^4, f_{T9}/Λ^4, f_{M2}/Λ^4, f_{M3}/Λ^4 parameters with and without additional selection on triboson mass for expected 40 fb^{-1} of 13 TeV proton-proton collisions data in ATLAS experiment from combination of $\mu^+\mu^-\gamma\gamma$ and $e^+e^-\gamma\gamma$ channels. No form factor unitarization is applied.

Expected limits 95%C.L.	$m(l^+l^-\gamma\gamma) > 0$ GeV	$m(l^+l^-\gamma\gamma) > 960$ GeV
f_{T9}/Λ^4 [TeV^{-4}]	$[-0.8, 0.8] \times 10^4$	$[-0.24, 0.24] \times 10^4$
f_{T5}/Λ^4 [TeV^{-4}]	$[-1.2, 1.2] \times 10^3$	$[-0.24, 0.25] \times 10^3$
f_{T0}/Λ^4 [TeV^{-4}]	$[-1.3, 1.4] \times 10^2$	$[-0.4, 0.5] \times 10^2$
f_{M2}/Λ^4 [TeV^{-4}]	$[-0.3, 0.3] \times 10^5$	$[-0.9, 0.9] \times 10^4$
f_{M3}/Λ^4 [TeV^{-4}]	$[-0.5, 0.5] \times 10^5$	$[-1.7, 1.6] \times 10^4$

4. Study of unitarity and unitarized limits

To preserve S-matrix unitarity and EFT validity at high energies [1] the dipole form factor

$$F(s) = \frac{1}{(1 + \hat{s}/\Lambda_{FF}^2)^n} \tag{3}$$

is implemented in `VBFNLO` [5]. It manually suppresses the cross section back to the unitarity bounds. The default exponent for aQGC is $n = 2$. To choose Λ_{FF} parameter value the dependencies of unitarity bounds (UBs) and expected limits on Λ_{FF} for favored parameters f_{T0}/Λ^4 and f_{T9}/Λ^4 are studied. They are shown in figure 3. Here UBs are estimated from the scattering of bosons corresponding to the aQGC vertex as the maximum allowed Λ_{FF} for up to 13 TeV energy [5, 11, 12]. Region where expected limits lay below the UB, preserves unitarity at current $\sqrt{\hat{s}}$. To obtain the most stringent limits we chose the highest allowed Λ_{FF} scale. Unitarized limits with chosen Λ_{FF} are presented in table 2.

Table 2. Unitarized expected limits on f_{T0}/Λ^4 and f_{T9}/Λ^4 parameters for expected 40 fb^{-1} of 13 TeV proton-proton collisions data in ATLAS experiment from combination of $\mu^+\mu^-\gamma\gamma$ and $e^+e^-\gamma\gamma$ channels.

95%C.L.	Expected limits [TeV^{-4}]	Λ_{FF} [TeV]
f_{T0}/Λ^4	$[-2.5, 2.3] \times 10^3$	0.7
f_{T9}/Λ^4	$[-1.7, 1.7] \times 10^5$	0.7

(a)   (b)

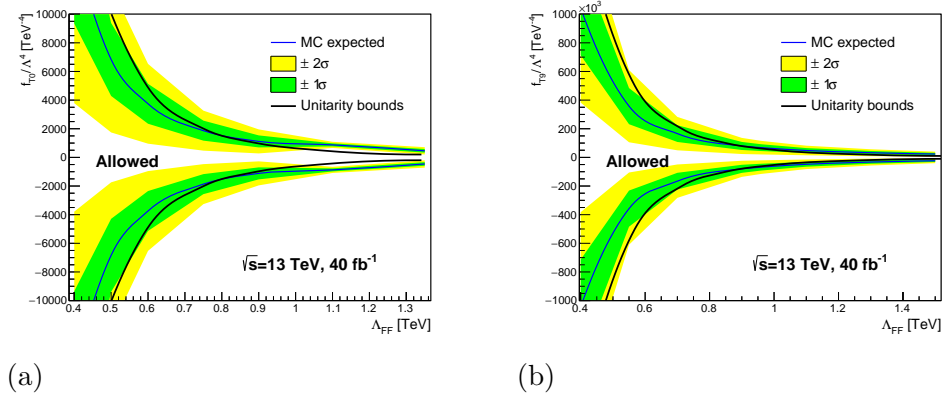**Figure 3.** Dependencies of the expected limits and unitarity bounds on the form factor scale Λ_{FF} for f_{T0}/Λ^4 (a) and f_{T9}/Λ^4 (b). The green and yellow bands show expected limits variation by 1σ and 2σ, respectively. Form factor scale 0.7 TeV is chosen for both parameters.

5. Comparison to previous experimental results

To perform comparison of expected limits with currently known observed limits, results are transformed in common Éboli formalism [13]. The f_{T0}/Λ^4, f_{T5}/Λ^4, f_{T9}/Λ^4, f_{M2}/Λ^4 and f_{M3}/Λ^4 in comparison with recent ATLAS [4, 14] and CMS [15] experiments can be found in figure 4. No form factor is applied to all these limits.
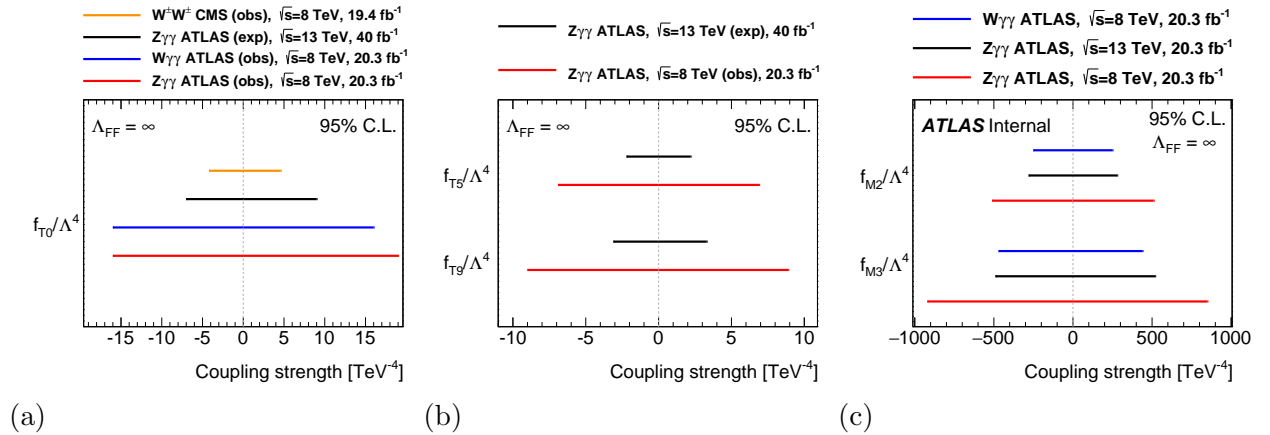

(a)   (b)   (c)

Figure 4. Comparison of the current observed limits from ATLAS [4, 14] and CMS [15] experiments and expected limits for expected 40 fb^{-1} of 13 TeV proton-proton collisions data in ATLAS experiment without form factor unitarization for f_{T0}/Λ^4 (a), for f_{T5}/Λ^4 and f_{T9}/Λ^4 (b) and for f_{M2}/Λ^4 and f_{M3}/Λ^4 (c).

6. Summary

Expected limits on f_{T0}/Λ^4, f_{T5}/Λ^4, f_{T9}/Λ^4, f_{M2}/Λ^4, f_{M3}/Λ^4 are obtained for prospective 40 fb^{-1} data of 13 TeV proton-proton collisions from combination of $\mu^+\mu^-$ and e^+e^- channels of Z boson decay in $Z\gamma\gamma$ associated production. They show significant improvement in comparison with $Z\gamma\gamma$ 8 TeV analysis results [4], but f_{T0}/Λ^4, f_{M2}/Λ^4 and f_{M3}/Λ^4 still have not the most stringent limits, since there are some processes, which are more sensitive to these parameters. Also the unitarity is studied for f_{T0}/Λ^4, f_{T9}/Λ^4 parameters using dipole form factor approach,

which is implemented in VBFNLO. For both of the parameters unitarity is preserved with $\Lambda_{FF} = 0.7$ TeV and $n = 2$ for $\sqrt{\hat{s}}$ up to 13 TeV.

Acknowledgments

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