PROCEEDINGS OF SCIENCE

# Methodology of accounting for aQGC effect on background for improvement of the limits on EFT coupling constants in case of electroweak $Z\gamma$ production at the conditions of Run2 at the ATLAS experiment

**Artur Semushin**[a,*] **and Evgeny Soldatov**[a]

[a] *National Research Nuclear University MEPhI,*
*115409, Moscow, Russia*

*E-mail:* Artur.Semushin@cern.ch, EYSoldatov@mephi.ru

In this report the model-independent effective field theory phenomenology is used to parameterize the anomalous couplings in the Lagrangian with higher-dimensional operators. Setting limits on the operator's coefficients (EFT coupling constants) leads to new physics constraints. The decomposition technique of MC event generator MG5_aMC is used to produce events corresponding separate terms of the full amplitude. In the classical version of setting these limits, all background processes are considered as non-depending on coefficients. However in general case one or several backgrounds can be affected by non-zero EFT coupling constants. This report presents the way of accounting such background impact in limits setting. As an example the electroweak $Z\gamma$ production is considered, since this process is extremely sensitive to anomalous quartic gauge couplings. As a result the limits on the EFT coefficients $f_{T0}$ and $f_{M0}$ were obtained with accounting of the possible new physics in the electroweak $W\gamma$ production background, which are 1% and 5% tighter respectively than classical ones.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

[*] Speaker



https://pos.sissa.it/

PoS(PANIC2021)127

## 1. Introduction, effective field theory and methodology description

By comparing theoretical predictions with experimental data one can test the Standard Model (SM) and search for the manifestations of new physics. It is convenient to use a modern model-independent approach of effective field theory (EFT) [1] for indirect search of new physics. This approach is based on parameterization of the currently unaccesible high energy effects of possible new physics in the Lagrangian with operators of higher dimensions with some coefficients:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \sum_n \frac{F_{i,n}}{\Lambda^n} O_i^{n+4} = \mathcal{L}_{\text{SM}} + \sum_i \sum_n f_{i,n} O_i^{n+4}, \tag{1}$$

where $\mathcal{L}_{\text{SM}}$ is the SM Lagrangian, $\Lambda$ is the new physics energy scale, $O_i^{n+4}$ is the $i$-th operator of $n+4$ dimension, $F_{i,n}$ is the corresponding dimensionless coefficient, $f_{i,n} = F_{i,n}/\Lambda^n$ is the corresponding (Wilson) coefficient which has dimension TeV$^{-n}$. Limits on these coefficients (or EFT coupling constants) lead to new physics constraints. This kind of study allows to find out a right direction for the SM extension.

If the Lagrangian is parameterized with two operators, the squared amplitude contains the SM term, 2 interference terms, 2 quadratic terms and a cross term, which corresponds to the interference between 2 EFT operators:

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\text{SM}} + f_1 O_1 + f_2 O_2 \longrightarrow |\mathcal{A}|^2 = |\mathcal{A}_{\text{SM}}|^2 + f_1 \cdot 2\text{Re}\,\mathcal{A}^\dagger_{\text{SM}}\mathcal{A}_{\text{BSM},1} + f_1^2|\mathcal{A}_{\text{BSM},1}|^2 + \\ + f_2 \cdot 2\text{Re}\,\mathcal{A}^\dagger_{\text{SM}}\mathcal{A}_{\text{BSM},2} + f_2^2|\mathcal{A}_{\text{BSM},2}|^2 + f_1 f_2 \cdot 2\text{Re}\,\mathcal{A}^\dagger_{\text{BSM},1}\mathcal{A}_{\text{BSM},2}.\end{aligned} \tag{2}$$

In the classical procedure of setting such limits, all background processes are considered as non-depending on EFT coefficients, so Eq. (2) is used only for the signal process and other processes have only the SM term. However, in general case one or several backgrounds can be also affected by non-zero EFT coupling constants, leading to changes in the total interference and quadratic terms. The resulting limits are more correct and can be tighter.

## 2. Example model: electroweak $Z\gamma$ production

In this work the methodology described in the previous section was applied to the electroweak $Z\gamma$ production ($Z\gamma$ EWK) with $Z$ boson decaying to neutrinos. This process is very sensitive to anomalous quartic gauge couplings (aQGC) and the high branching ratio of the $Z$ boson decay to two neutrinos makes this final state one of the most sensitive. It can contain either quartic gauge boson vertex predicted by the SM ($WWZ\gamma$) or anomalous quartic vertices (aQGCs), which can be present only in new physics theories ($ZZZ\gamma$, $ZZ\gamma\gamma$, $Z\gamma\gamma\gamma$). Further consideration was performed with an example of two 8-dimensional operators of different types by their construction:

$$O_{\text{T0}} = \text{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \text{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right], \quad O_{\text{M0}} = \text{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right]\left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right]. \tag{3}$$

In the toy model for this work only 3 background processes were taken into account: strong $Z\gamma$ production ($Z\gamma$ QCD), electroweak and strong $W\gamma$ production ($W\gamma$ EWK and $W\gamma$ QCD), where $W\gamma$ EWK is sensitive to the operators mentioned in Eq. (3). Examples of diagrams of $Z\gamma$ EWK and QCD can be found in Fig. 1.

All considered processes were generated using $pp$-collisions with center of mass energy of 13 TeV in Monte Carlo (MC) event generator MadGraph5_aMC@NLO [2]. Pythia8 [3] was used for parton showering and hadronization and Delphes3 [4] was used for detector simulation. The Run2 integrated luminosity of 139 fb$^{-1}$ was used for the calculations in this study. The event selection


**Figure 1:** Examples of diagrams for $Z\gamma$ EWK (left) and $Z\gamma$ QCD (right) production processes.

criteria used in this work were derived from the ATLAS Run1 study [5] and are presented in Table 1. Illustrations of kinematic distributions can be found in Fig. 2. To simplify statistical model, one total uncertainty of 20% was used, which approximately includes ATLAS Run1 systematic and MC statistical uncertainties.

**Table 1:** Event selection criteria[1].

| |
|---|
| $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV, $p_{\mathrm{T}}^{\mathrm{balance}} < 0.1$, $p_{\mathrm{T}}^{\gamma} > 150$ GeV, $\lvert\eta_\gamma\rvert < 2.37$, $\zeta_\gamma < 0.3$ |
| $N_{\mathrm{leptons}} = 0$, $N_{\mathrm{jets}} \geq 2$, $E_{\mathrm{T}}^{j} > 30$ GeV, $m_{jj} > 600$ GeV, $\lvert\Delta y_{jj}\rvert > 2.5$ |
| $\lvert\Delta\varphi(E_{\mathrm{T}}^{\mathrm{miss}}, \gamma jj)\rvert > \frac{3\pi}{4}$, $\lvert\Delta\varphi(E_{\mathrm{T}}^{\mathrm{miss}}, \gamma)\rvert > \frac{\pi}{2}$, $\lvert\Delta\varphi(E_{\mathrm{T}}^{\mathrm{miss}}, j)\rvert > 1$ |

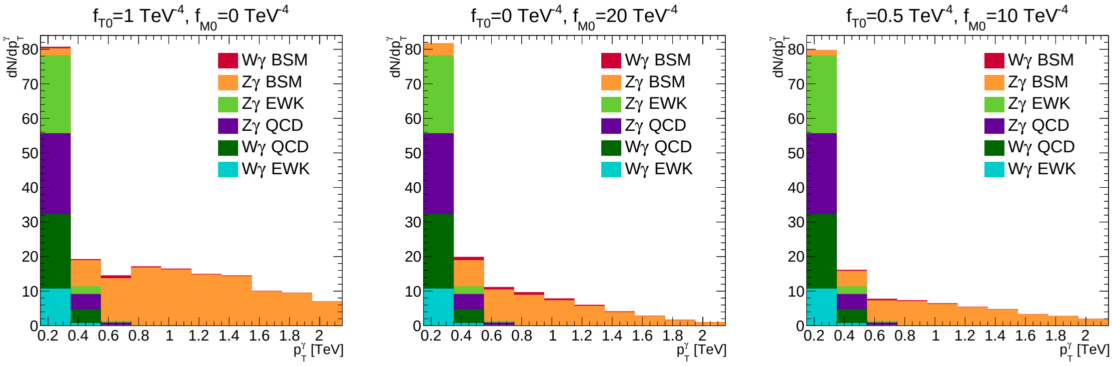


**Figure 2:** $p_{\mathrm{T}}^{\gamma}$ distributions showing contributions of SM and BSM (beyond-the-SM) terms.

## 3. Results and summary

In the limit-setting procedure the test statistic $t_{\mu} = -2\ln\lambda(\boldsymbol{\mu})$ was used, where $\boldsymbol{\mu}$ is a single coefficient ($f_{\mathrm{T0}}$ or $f_{\mathrm{M0}}$) in case of 1D limits or the vector $\boldsymbol{\mu} = (f_{\mathrm{T0}}, f_{\mathrm{M0}})$ in case of 2D limits and $\lambda(\boldsymbol{\mu})$ is the profile likelihood ratio [6]. As a statistical method for setting 95% CL ($\alpha = 1 - \mathrm{CL} = 0.05$) limits the CL$_{s+b}$ technique was used, which consists in finding $\boldsymbol{\mu}$ region, where the $p$-value

$$p_{\mu} = \int_{t_{\mu}^{\mathrm{obs}}}^{\infty} f(t_{\mu}|\boldsymbol{\mu})\,\mathrm{d}t_{\mu} > \alpha = 0.05, \tag{4}$$

where $t_{\mu}^{\mathrm{obs}}$ is the observed value of the test statistic and $f(t_{\mu}|\boldsymbol{\mu})$ is the test statistic distribution under the $\boldsymbol{\mu}$ hypothesis (i.e. the hypothesis that the data corresponds to the value of $\boldsymbol{\mu}$), which was assumed as asymptotic (i.e. chi-squared with number of degrees of freedom equal to parameter-of-interest space dimensionality, according to Wilks' theorem). The resulting limits can be found in Table 2 (1D $f_{\mathrm{T0}}$, $f_{\mathrm{M0}}$) and in Fig. 3 (2D $f_{\mathrm{T0}}$ vs $f_{\mathrm{M0}}$).

[1] $p_{\mathrm{T}}^{\mathrm{balance}} = \frac{\lvert\vec{p}_{\mathrm{T}}^{\mathrm{miss}}+\vec{p}_{\mathrm{T}}^{\gamma}+\vec{p}_{\mathrm{T}}^{j_1}+\vec{p}_{\mathrm{T}}^{j_2}\rvert}{E_{\mathrm{T}}^{\mathrm{miss}}+p_{\mathrm{T}}^{\gamma}+p_{\mathrm{T}}^{j_1}+p_{\mathrm{T}}^{j_2}}$ — $p_{\mathrm{T}}$-balance, $\zeta_\gamma = \left|\frac{\eta_\gamma-(\eta_{j_1}+\eta_{j_2})/2}{\eta_{j_1}-\eta_{j_2}}\right|$ — centrality of the photon, $m_{jj}$ — invariant mass of the two leading jets, $y$ and $\eta$ — rapidity and pseudorapidity.

**Table 2:** Resulting 1D $f_{T0}$ and $f_{M0}$ limits.

| Coefficient | Only $Z\gamma$ EFT | $Z\gamma$ and $W\gamma$ EFT |
|---|---|---|
| $f_{T0}$ | [-0.752; 0.714] | [-0.750; 0.706] |
| $f_{M0}$ | [-22.1; 22.2] | [-21.1; 21.5] |

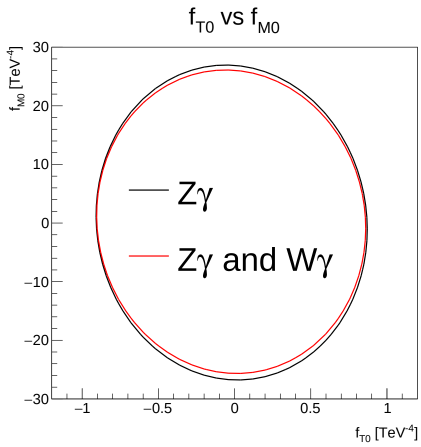


**Figure 3:** Resulting 2D $f_{T0}$ vs $f_{M0}$ limits.

Accounting for EFT effects on background gives tighter limits (improvement: $f_{T0}$ — 1%, $f_{M0}$ — 5%), although improvement depends on the sensitivity of background process to the considered EFT operators and phase space. Phase space optimization for combination of $Z\gamma$ and $W\gamma$ EFT signals can lead to larger improvement of the limits.

## Acknowledgements

This work is supported by the Russian Science Foundation under grant 21-72-10113.

## References


[1] C. Degrande, N. Greiner, W. Kilian, O. Mattelaer, H. Mebane, T. Stelzer et al., *Effective Field Theory: A Modern Approach to Anomalous Couplings*, Annals Phys. **335** (2013) 21 [1205.4231].

[2] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP **07** (2014) 079 [1405.0301].

[3] T. Sjöstrand, *The PYTHIA Event Generator: Past, Present and Future*, Comput. Phys. Commun. **246** (2020) 106910 [1907.09874].

[4] DELPHES 3 collaboration, *DELPHES 3, A modular framework for fast simulation of a generic collider experiment*, JHEP **02** (2014) 057 [1307.6346].

[5] ATLAS collaboration, *Studies of $Z\gamma$ production in association with a high-mass dijet system in $pp$ collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector*, JHEP **07** (2017) 107 [1705.01966].

[6] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, Eur. Phys. J. C **71** (2011) 1554 [1007.1727].