Optimal observables as a probe of CP violation in the qq→Zγ→ννγ process

N. Belyaev, E. Soldatov

National Research Nuclear University MEPhI, Russia

Abstract

A possible CP violation effects in neutral currents are predicted in a wide class of theories Beyond the Standard Model (BSM). If such a violation will be discovered, it may shed light on the problem of the baryon asymmetry of the Universe. In this paper, an Effective Field Theory (EFT) approach is used to parameterize the BSM Zγ interaction. The optimal observables technique is applied to probe the CP even and CP odd anomalous EFT operator within the nTGC phenomenological model. Additional cut requirements on the photon transverse momentum p_T were considered in order to enhance the possible BSM signal.

Motivation

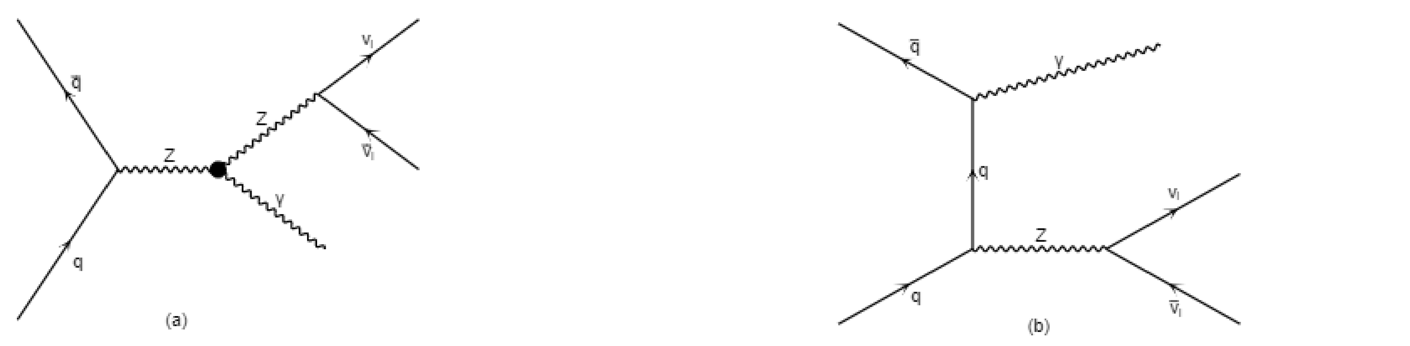
Anomalous couplings of electroweak bosons can serve as clear signs of the Beyond the Standard Model physics. The search for such couplings is usually being curried based on precise cross-section measurements of the Standard Model (SM) processes. Neutral ZZγ and Zγγ vertices are forbidden in the SM and the corresponding anomalous couplings can be probed by the study of associated production of a Z boson with a photon. These studies were performed by the high energy physics experiments [1,2,3]. The obtained results have shown no evidence for anomalous properties of neutral gauge bosons and have placed the limits on the anomalous couplings.

Methodology

For this study, the Effective Field Theory (EFT) approximation has been used. The main idea of the EFT approach is to use the Standard Model Lagrangian enhanced by BSM operators of higher dimension:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots,$$

This study is concentrated on neutral ZZγ and Zγγ couplings probed by Z(→$\bar{\nu}$ν)γ final state. This final state was chosen among the others providing good balance between reachable purity and probability among all decay channels. The Feynman diagrams of $\bar{q}$q→$\bar{\nu}$νγ process with neutral ZZγ BSM vertex and its SM background are shown below.



Feynman diagram of the leading-order $\bar{q}$q→$\bar{\nu}$νγ signal process involving BSM ZZγ vertex (a) and the corresponding SM background (b).

Several kinematic observables, like p_T(γ), η(γ) or cosine of Z polar angle, are widely used for the anomalous couplings experimental search [4]. The efficiency of these variables is ensured by the expectation that high energy BSM particles exist in the inaccessible energy range. Moreover, one can construct the additional so-called optimal observables, which are not based on kinematics, but on dynamics of the signal processes. For instance, the observables can have different shapes in case of presence of CP-even and/or CP-odd anomalous coupling in the Lagrangian. The optimal observables can provide an additional sensitivity for the anomalous couplings search and can be used together with already mentioned ones. Also these variable scan be used to determine the structure of the signal interaction vertex.

Optimal observables definition

In order to enhance the sensitivity of the search for the anomalous couplings one can use the optimal observables technique. The distributions of such observables usually have clear difference in case of presence of BSM anomalous part in the theory's Lagrangian. The idea of the optimal observables can be illustrated as follows. If the amplitude of some signal process M_{MIX} consists of separable M_{SM} and M_{BSM} parts, we can write the resulting squared matrix element as:

$$M_{MIX}^2 = (M_{SM} + M_{BSM})^2 = M_{SM}^2 + 2\Re(M_{SM}M_{BSM}) + M_{BSM}^2; \quad (1)$$

Let's then divide both parts of equation (1) by M_{SM}^2:

$$\frac{M_{MIX}^2}{M_{SM}^2} = 1 + \frac{2\Re(M_{SM}M_{BSM})}{M_{SM}^2} + \frac{M_{BSM}^2}{M_{SM}^2}; \quad (2)$$

Finally, the optimal observables can be defined as follows:

$$OO_1 = \frac{2\Re(M_{SM}M_{BSM})}{M_{SM}^2};\ OO_2 = \frac{M_{BSM}^2}{M_{SM}^2}. \quad (3)$$

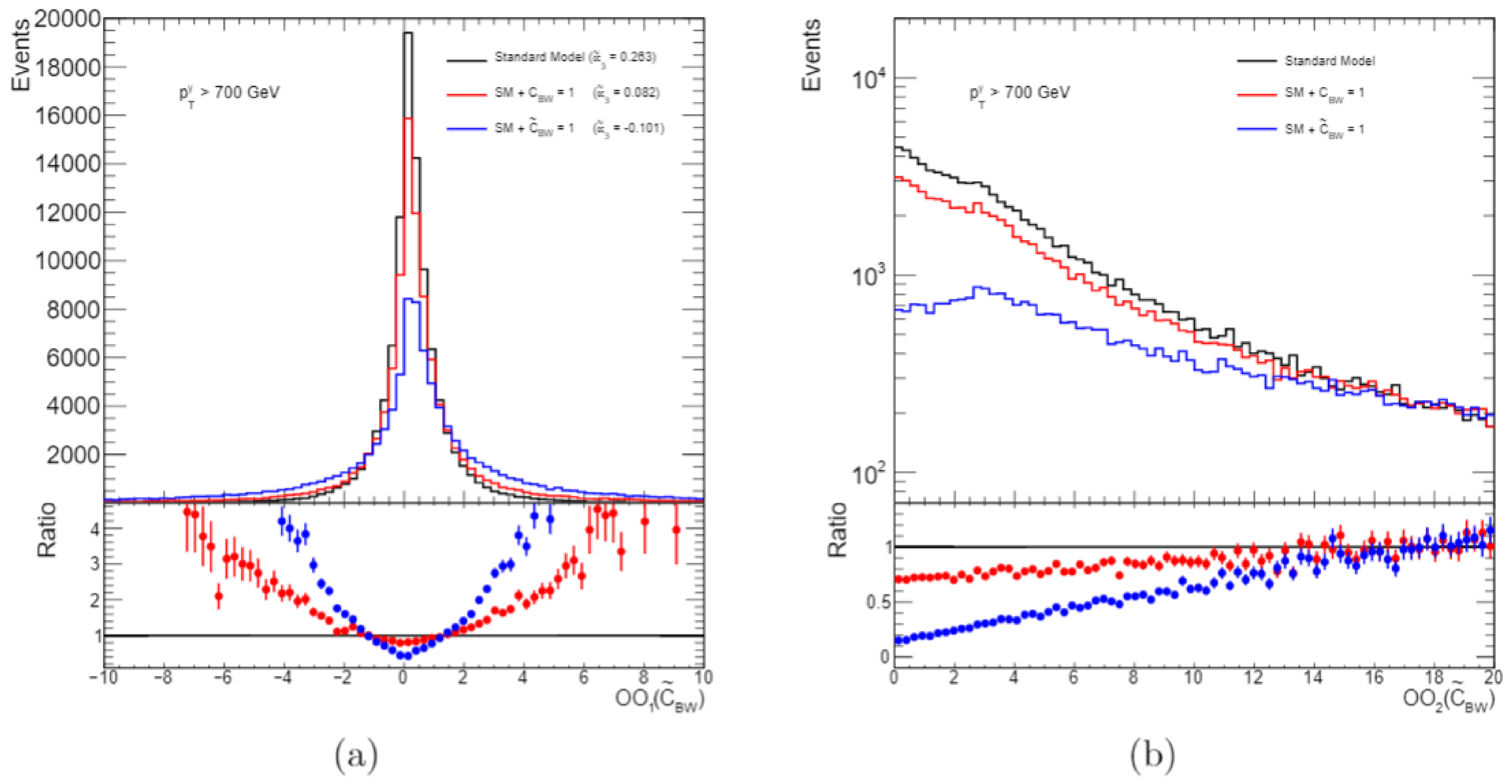
Thus the optimal observables represent linear and quadratic corrections to the SM matrix element in case of presence of additional BSM contributions. In case if only one additional BSM coupling is considered, the observable OO_1 is also sensitive to the sign of this coupling. This technique is widely used in the Higgs boson studies [5], but it was never tested in case of the EFT-based ZZγ interactions.

Monte Carlo simulations

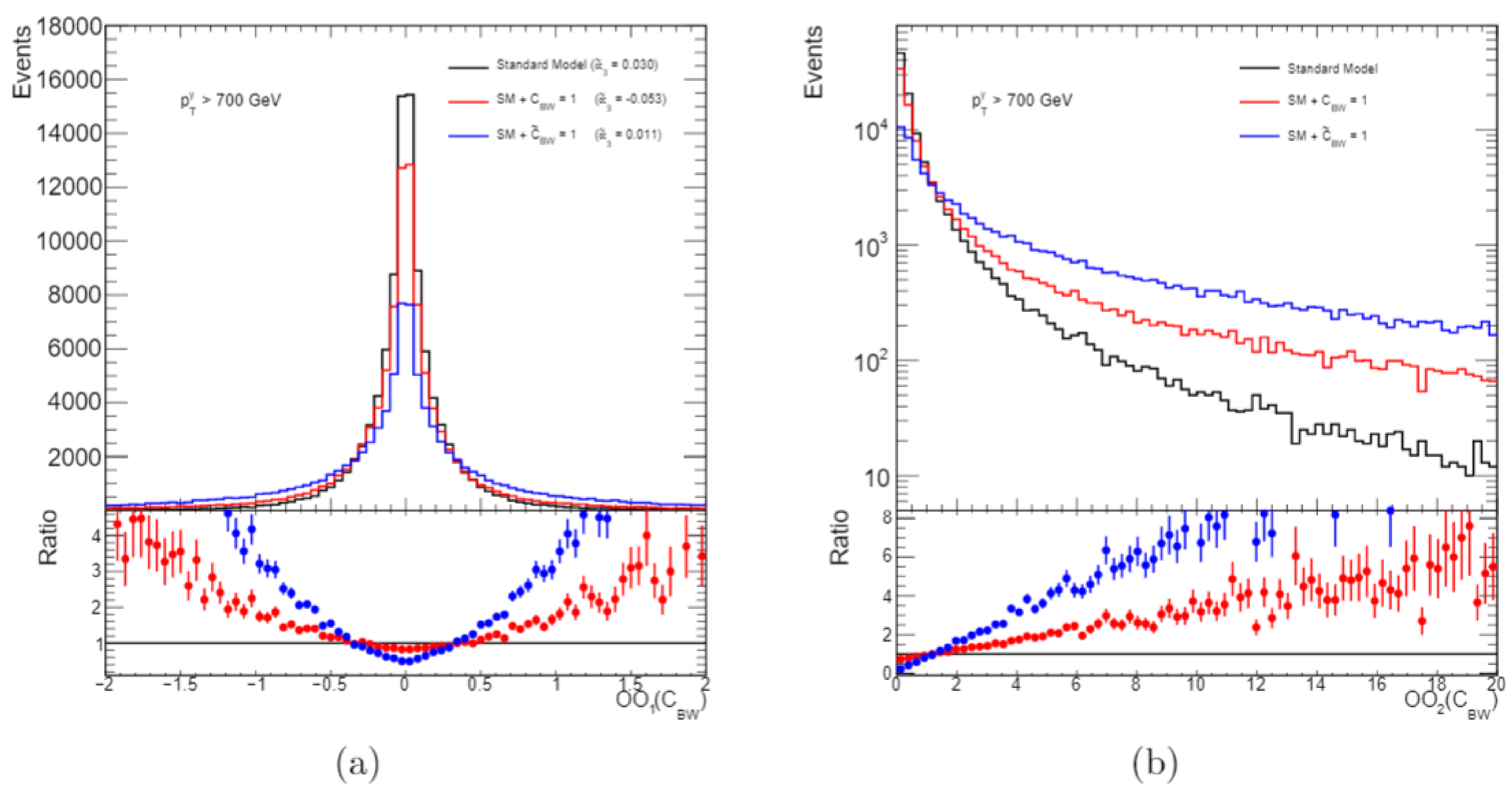
For this study, NTGC phenomenological model for the MadGraph5 generator was used [6]. In this model, the Zγ amplitude can be parameterized by three different CP-violating dimension-eight operators O_{BB}, O_{BW}, O_{WW} and one CP-conserving operator $\tilde{O}_{BW}$.

Three Monte Carlo samples were generated with 100k events each. Sample 1 corresponds to the SM case, Sample 2 corresponds to the case of SM plus CP-even EFT operator with $\tilde{C}_{BW}$= 1, Sample 3 corresponds to the SM plus CP-odd operator with C_{BW}= 1. Additional selection on photon transverse momentum was applied in order to enhance the possible BSM signal: p_T(γ)>700 GeV.

The results of simulation are shown below. One can see that optimal observables tuned to both CP-even and CP-odd couplings demonstrate visibly higher sensitivity to the $\tilde{C}_{BW}$ coupling that to C_{BW}. The reason is that at the current level of experimental limits on EFT couplings, configuration SM plus ($\tilde{C}_{BW}$= 1) has much higher cross section compared to the configuration SM plus (C_{BW}= 1): 0.795 fb versus 0.161 fb, respectively. The SM case has the cross section equals to 0.112 fb.



The distributions of the observables OO_1 (a) and OO_2 (b), tuned to the CP-even coupling $\tilde{C}_{BW}$. The distributions were calculated for three coupling configurations: SM, SM + (C_{BW}= 1) and SM + ($\tilde{C}_{BW}$ = 1). The skewness values $\tilde{\mu}_3$ are also shown for each case of OO_1 distribution.



The distributions of the observables OO_1 (a) and OO_2 (b), tuned to the CP-odd coupling C_{BW}. The distributions were calculated for three coupling configurations: SM, SM + (C_{BW}= 1) and SM + ($\tilde{C}_{BW}$ = 1). The skewness values $\tilde{\mu}_3$ are also shown for each case of OO_1 distribution.

Conclusions

The optimal observables technique was applied to probe anomalous CP-even and CP-odd couplings in the ZZγ vertex. Obtained results demonstrate the separation power of the optimal observables and they can be used to enhance the sensitivity of the anomalous couplings search. At the current level of experimental limits it is possible to place more strict constrains on the CP-even EFT operator with C_{BW} by using the optimal observables.

Acknowledgements

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