Optimal observables as a probe of CP violation in the \( q\bar{q} \rightarrow Z\gamma \rightarrow \nu\bar{\nu}\gamma \) process

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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 \( Z\gamma \) 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.

1. Introduction
Anomalous couplings of electroweak bosons, which are forbidden in the Standard Model (SM), can serve as clear signs of the Beyond the Standard Model (BSM) physics in case their non-zero values will be measured. The search for such couplings is usually being carried based on precise cross-section measurements of the SM processes.

These days, there are many theoretical and experimental studies related to the anomalous effects in the neutral currents \([1–4]\). Searches for possible CP violation in the neutral currents are very important part of that studies due to possible consequences in case of discovery of such effect. If CP violation in the neutral currents exists, it will become the first observation of so-called new physics and might be a key to understanding the baryon asymmetry of the Universe.

Neutral \( ZZ\gamma \) and \( Z\gamma\gamma \) 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 at the LHC \([5,6]\), Tevatron \([7,8]\) and LEP \([9,11]\). The obtained results have not yet shown any evidences for anomalous properties of neutral gauge bosons and have placed the limits on the anomalous couplings.

2. Methodology
This paper is concentrated on neutral \( ZZ\gamma \) and \( Z\gamma\gamma \) couplings probed in \( Z \rightarrow \nu\bar{\nu}\gamma \) final state. This final state was chosen among the others since, from one side, provides the lower background contamination than \( Z \rightarrow q\bar{q}\gamma \) final state, and, from the other side, has higher branching ratio than \( Z \rightarrow ll\gamma \) final state \([12]\). The Feynman diagrams of \( q\bar{q} \rightarrow \nu\bar{\nu}\gamma \) process with neutral \( ZZ\gamma \) BSM vertex and its dominant SM background are shown in figure 1.
Several kinematic observables, like photon transverse momentum $p_T^\gamma$, photon pseudorapidity $\eta_\gamma$ or cosine of the $Z$ boson polar angle $\cos \Theta^*$, are widely used for the experimental searches of the anomalous couplings \[13\]. The choice of these variables is based on the assumption that high energy BSM particles exist in the inaccessible energy range.

Moreover, one can construct additional so-called optimal observables, which are based not on kinematics, but on dynamics of the signal processes \[15\]. For instance, these observables can have different shapes in case of presence of CP-even and/or CP-odd anomalous operators in the theory’s Lagrangian. The optimal observables can provide an additional sensitivity of the anomalous couplings searches and can be used together with already mentioned variables. Also, the optimal observables can be used to determine the structure of the signal interaction vertex.

### 3. Optimal observables definition

In order to enhance the sensitivity of the searches 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 parts in the theory’s Lagrangian.

The idea of the optimal observables can be illustrated as follows. If the amplitude of some signal process $M_{\text{MIX}}$ consists of separate $M_{\text{SM}}$ and $M_{\text{BSM}}$ parts, the resulting squared matrix element can be written as follows:

$$M^2_{\text{MIX}} = (M_{\text{SM}} + M_{\text{BSM}})^2 = M^2_{\text{SM}} + 2\Re(M_{\text{SM}}M_{\text{BSM}}) + M^2_{\text{BSM}};$$

(1)

Let’s then divide both parts of equation (1) by $M^2_{\text{SM}}$:

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

(2)

Finally, the optimal observables can be defined as follows:

$$OO_1 = \frac{2\Re(M_{\text{SM}}M_{\text{BSM}})}{M^2_{\text{SM}}} = \frac{M^2_{\text{MIX}}}{M^2_{\text{SM}}} - \frac{M^2_{\text{BSM}}}{M^2_{\text{SM}}};$$

$$OO_2 = \frac{M^2_{\text{BSM}}}{M^2_{\text{SM}}}.$$

(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 that coupling. This technique is widely used in the Higgs boson studies \[15\], but it was never tested in case of the $ZZ\gamma$ interactions.
Figure 2. The distributions of the observables $OO_1$ (a) and $OO_2$ (b), tuned to the CP-even coupling $c_{BW}$. The distributions were calculated for three coupling configurations: SM, SM + ($c_{BW} = 1$) and SM + ($c_{BW} = 1$). The skewness values $\tilde{\mu}_3$ and their standard errors are also shown for each case of $OO_1$ distribution.

Figure 3. 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 + ($c_{BW} = 1$). The skewness values $\tilde{\mu}_3$ and their standard errors are also shown for each case of $OO_1$ distribution.
4. Monte Carlo simulation

According to the EFT approach, at low energies, any extension of the SM can be described by the effective Lagrangian:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{D>4} \sum_i c_i^{(D)} \Lambda^{D-4} O_i^{(D)}, \]

where \( D \) is the dimension of the EFT operator \( O_i^{(D)} \) and \( \Lambda \) is the characteristic energy scale of the new physics. The new operators are built out of the SM fields and preserve its gauge symmetries. The \( c_i^{D} \) are coefficients corresponding to these operators called Wilson coefficients.

For this study, NTGC phenomenological model of the MadGrapg5 Monte Carlo (MC) generator was used [14, 16]. In this model, the \( Z\gamma \) amplitude can be parameterized by three different CP-odd dimension-eight operators \( O_{BB}, O_{BW}, O_{WW} \) and one CP-even operator \( \tilde{O}_{BW} \).

Three MC samples were generated with 100k events each. The first sample corresponds to the SM case. The second sample corresponds to the case of SM plus CP-even EFT operator with \( c_{\tilde{B}B} = 1 \). The third sample corresponds to the case of SM plus CP-odd operator with \( c_{BW} = 1 \). Additional selection requirement on photon transverse momentum was applied in order to enhance the possible BSM signal: \( p_T^\gamma > 700 \) GeV. The corresponding matrix elements required for the calculation of the optimal observables were also generated as a standalone C++ code by the MadGraph5 generator.

The results of simulation are shown in figures 2 and 3. One can see that optimal observables tuned to both CP-even and CP-odd couplings demonstrate visibly higher sensitivity to the \( c_{\tilde{B}B} \) coupling than to \( c_{BW} \). The reason is follows: at the current level of experimental constrains on the EFT couplings \( c_{\tilde{B}B} \) and \( c_{BW} \), configuration SM plus \( (c_{\tilde{B}B} = 1) \) 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.

5. Conclusions

The optimal observables technique was applied to probe anomalous CP-even and CP-odd couplings in the \( ZZ\gamma \) vertex. Obtained results demonstrate the separation power of the optimal observables and they can be used to enhance the sensitivity of the anomalous couplings searches. At the current level of experimental limits, it is possible to place more strict constrains on the EFT coupling \( c_{BW} \) and \( c_{\tilde{B}B} \) by using the optimal observables.

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