

# Probing anomalous off-shell electroweak dipole moment of the top quark in single top quark production associated with Z or W bosons

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**Abstract.** An extension of the previous studies of anomalous Wtb interaction with off-shell W boson was considered in associated single top quark production with W or Z bosons. More general variant with covariant derivative  $D^\mu W_\mu^- \bar{b}(f_W^L P_L + f_W^R P_R)t$  for the same processes is considered in this paper.

## 1 Introduction

A new physics may manifest itself through different ways. Many BSM theories predict new particles if the energy of collision is greater than the production threshold ( $E_{\text{collision}} > E_{\text{threshold}}$ ). However, even in the opposite scenario with ( $E_{\text{collision}} < E_{\text{threshold}}$ ) BSM physics could prove itself through anomalous couplings originating from higher dimensional gauge invariant operators or interference terms of new resonances with the SM particles, that leads to deviation from SM prediction in production cross sections and/or kinematic distributions. The top quark sector of SM owing to its unique properties such as large mass, small lifetime, spin correlations and very small mixing to the light quark generations, could be a window to BSM physics. The effective Lagrangian approach is commonly used in experimental physics for model-independent description of possible BSM effects. Thus, lowest-dimension Lagrangian [1] for the Wtb vertex usually written as:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (f_V^L P_L + f_V^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{\sigma^{\mu\nu} \partial_\nu W_\mu^-}{M_W} (f_T^L P_L + f_T^R P_R) t + \text{h.c.}, \quad (1)$$

where  $P_{L,R} = (1 \mp \gamma_5)/2$ ,  $\sigma_{\mu\nu} = i(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)/2$ ,  $g$  is the coupling constant of the weak interaction, the constant  $f_V^L$  represents the left-handed vector coupling, presented in SM,  $f_V^R$  is the anomalous right-handed vector coupling and  $f_T^L$  ( $f_T^R$ ) represents the anomalous left-handed (right-handed) tensor coupling. Such anomalous couplings nowadays are relatively well studied both theoretically [2]-[5] and experimentally [6]-[8].

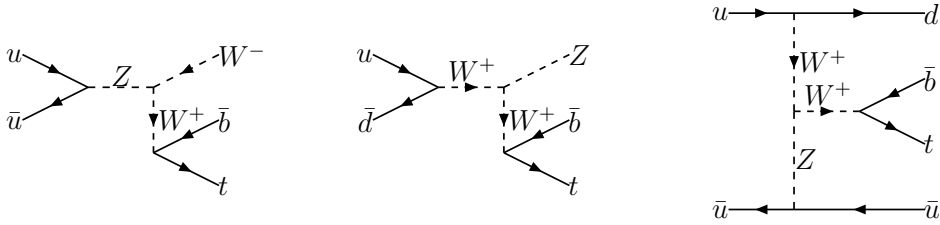
Different approaches [1, 9] could lead to an additional contributions, like off-shell electroweak dipole moment (osEDM)

$$\partial^\mu W_\mu^- \bar{b} P_L t,$$

phenomenologically studied in the previous article [10]. This time, we consider more complicated and physically reliable case, when partial derivative will be replaced with covariant derivative:

$$D^\mu W_\mu^- \bar{b}(f_W^L P_L + f_W^R P_R)t.$$

Such osEDM couplings are totally vanish in case of pair or main electroweak top quark production processes, but could make contribution to single top quark production associated with electroweak gauge bosons or via electroweak fusion diagrams (Fig. 1).



**Figure 1.** Feynman diagrams of the processes, which could be used to search for the anomalous off-shell W boson couplings.

## 2 Relevant processes

The effective Lagrangian used in the analysis has the following form:

$$\mathcal{L}_{eff} = \frac{g}{\sqrt{2}} \frac{v}{\Lambda^2} D^\mu W_\mu^- \bar{b}(f_W^L P_L + f_W^R P_R)t + \text{h.c.} \quad (2)$$

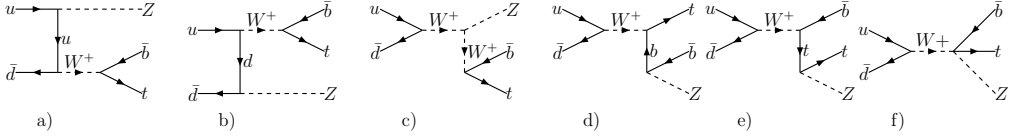
Here  $\frac{v}{\Lambda^2}$  corresponds to natural dimensional factor of the anomalous operators,  $v = 246$  GeV is vacuum expectation value,  $\Lambda$  is the scale of a new physics and constants  $f_W^L$  and  $f_W^R$  are the strengths of left and right anomalous couplings.

For studying processes with anomalous osEDM the CompHEP 4.5.2 package [11] was used to model kinematic distributions of the osEDM and SM contributions including their interference. The Feynman rules were generated with the LanHEP package [12], and implemented into CompHEP.

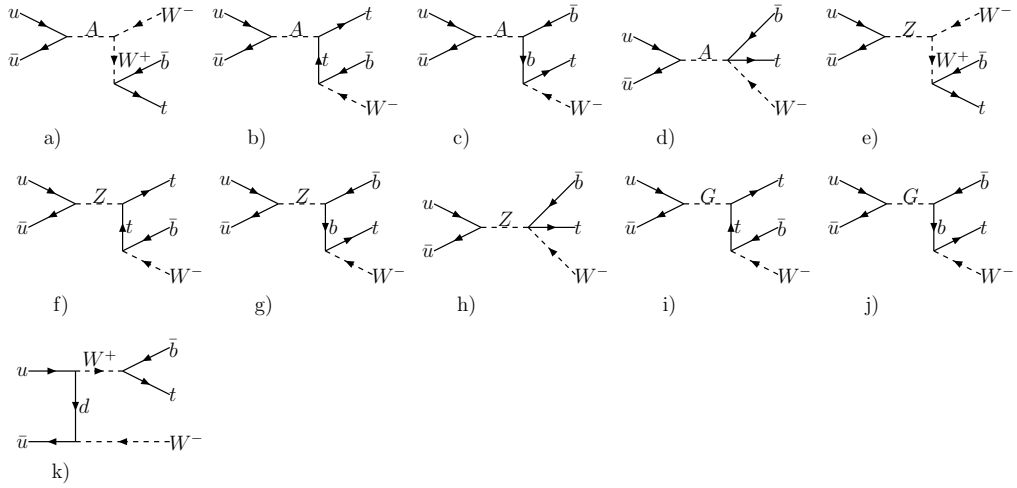
The complete set of electroweak diagrams for the associated tbZ and tbW production is shown in Fig. 2 and 3, correspondingly. While the most diagrams in both processes are presented in SM they are affected by the anomalous contributions. Diagrams f) on Fig. 2 and d) and h) on Fig. 3 contain a 4-particle vertexes, caused by the anomalous Lagrangian. In comparison with previous studies [10], sensitivity of tbZ process significantly fall off, but tbW final state becomes much more sensitive to anomalous contribution. As a result, tbW process is now looking more preferable to studying, despite it has significant background from top quark pair production and associated tW single top production, as it could be suppressed by exclusive cut on invariant mass of W boson and b quark system near top quark mass value.

## 3 Kinematic distribution and extracting potential

The kinematic cuts look even more effective, if note, that anomalous contribution nearly are not affected, because BSM contribution peaks on much higher energy (Fig. 4).



**Figure 2.** All relevant Feynman diagrams of the process of associated production of a top quark with Z boson.

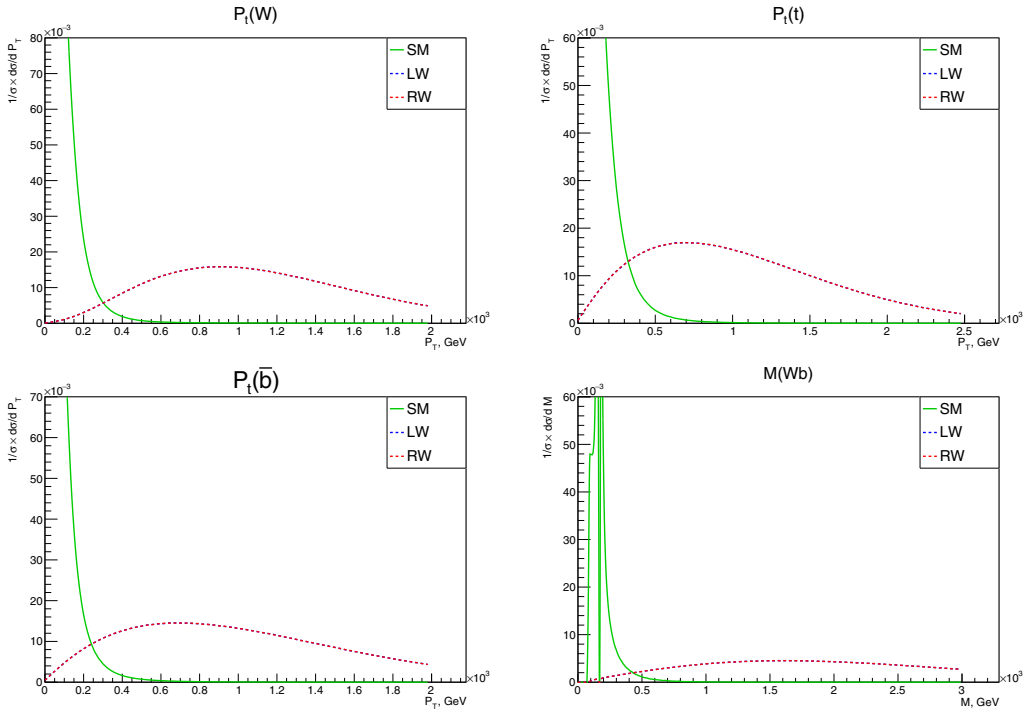


**Figure 3.** All relevant Feynman diagrams of the process of associated production of a top quark with W boson.

There are two explanations of such behavior of different energy distributions, the first is momenta dependence in osEDM Lagrangian itself. The second is the preferred space orientation of anomalous interaction, when the final state particles are mostly central and locate almost in transverse plane (Fig. 5)

The angular distributions (Fig. 6) of the final particles show that in case of SM production, top quark often co-directed with W boson and bottom quark, while in case of anomalous production both distributions are more smooth, with small prevailing of opposite directions.

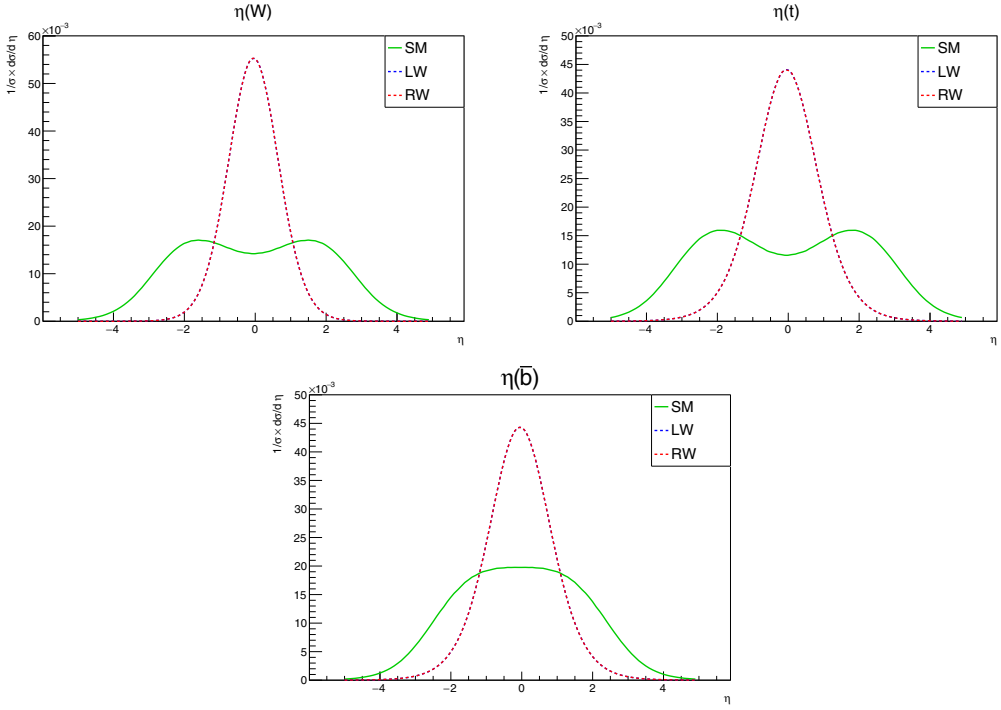
Although tbZ final state has much less cross section and sensitivity to anomalous interactions then associated production of a top quark with W boson, it has advantage in possibility to distinguish the left and right osEDM couplings from each other. While couplings have the same cross sections and kinematics in tbW final state, and comparing to previous studies, there is no visible interference term with SM part, in both tbW and tbZ processes, there is a small difference in anomalous contribution in tbZ process (Fig. 7). The difference is caused by diagrams a) and b) in the Fig 2, in the case of sea heavy quarks in the initial state, quarks of different flavors are taken into account for propagators of the initial virtual quark exchange.



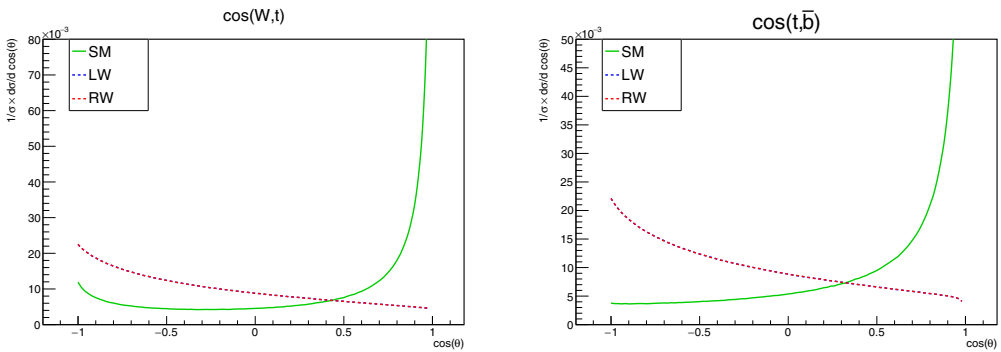
**Figure 4.** Transverse momentum distributions for the SM interaction (SM), with dominant  $gg$  initial state, and pure left (LW) and right (RW) osEDM, with the  $u\bar{u}$  initial state, in the process of associated production of a top quark with W boson. There are plots for W boson (top left), top quark (top right) and bottom quark (bottom left), and invariant mass for W and b (bottom right). Exclusive cut  $162 < m(Wb) < 183$  is used. The distributions of each coupling are normalized to the corresponding cross sections.

## 4 Conclusion

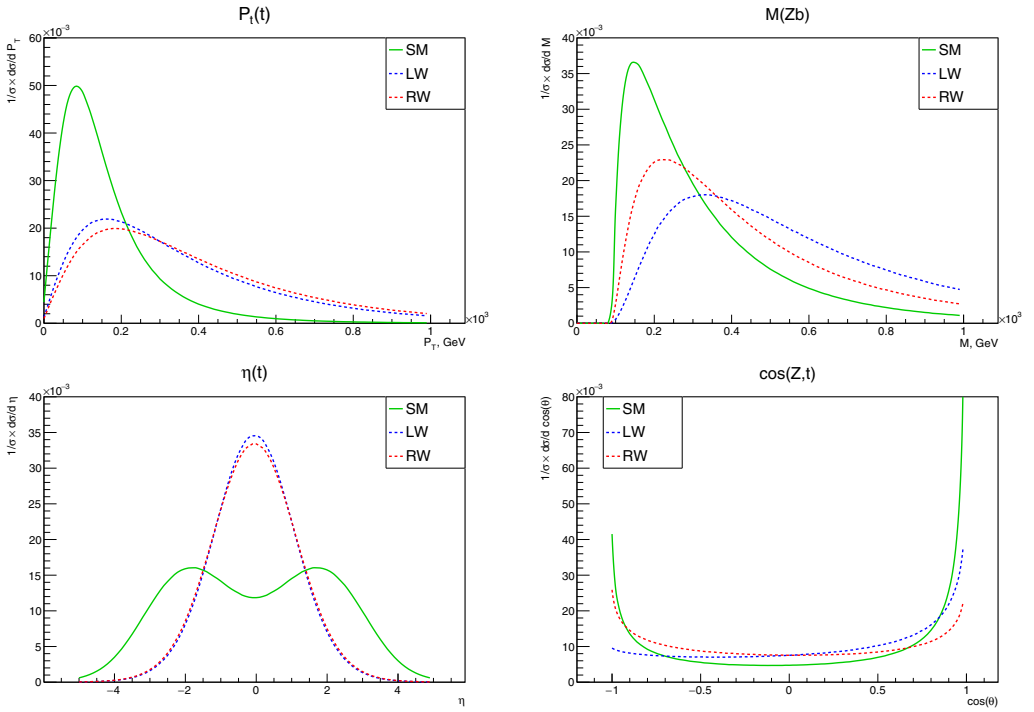
The paper extends previous phenomenological studies of possible anomalous osEDM interactions, using more general Lagrangian of such interactions. Single top quark production associated with Z or W bosons are considered for the processes with non-zero contribution from osEDM couplings. Necessary calculations of these processes have been performed using CompHEP package. The results demonstrate significant difference in the kinematic distributions, comparing to previous studies [10]. It is shown that process with  $tbW$  final state looks prospective for the search for the osEDM couplings. Even in the case of small coupling values the experiments can be sensitive for the anomalous interactions with the help of multivariate analysis methods, like artificial neural networks. The process of single top quark production associated with Z boson demonstrates difference in left and right anomalous interactions, however, due to relatively small cross section the experimental search for such contribution is difficult.



**Figure 5.** Pseudorapidity distributions for the SM interaction (SM), with dominant  $gg$  initial state, and pure left (LW) and right (RW) osEDM, with the  $u\bar{u}$  initial state, in the process of associated production of a top quark with W boson. The plots for W boson (top left), top quark (top right) and bottom quark (bottom) are shown. Exclusive cut  $162 < m(Wb) < 183$  is used. The distributions of each coupling are normalized to the corresponding cross sections.



**Figure 6.** Angular distributions of the SM interaction (SM), with dominant  $gg$  initial state, and pure left (LW) and right (RW) osEDM, with the  $u\bar{u}$  initial state, in the process of associated production of a top quark with W boson are shown. There are plots for cosine of angle between W boson and top quark (left), and cosine of angle between top and bottom quarks (right). Exclusive cut  $162 < m(Wb) < 183$  is used. The distribution of each coupling is normalized to the corresponding cross section.



**Figure 7.** Distributions for the SM interaction (SM), with the dominant  $u\bar{d}$  initial state, left osEDM (LW), and right anomalous coupling (RW), in the process of associated production of a top quark with Z boson with the  $c\bar{s}$  initial state. There are plots for transverse momentum (top left) and pseudorapidity (bottom left) of top quark, invariant mass for Z boson and b quark (top right), and cosine of angle between Z boson and top quark (bottom right). The distributions of each coupling are normalized to the corresponding cross sections.

## 5 Acknowledgements

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