EPJ Web of Conferences **158**, 04004 (2017)
QFTHEP 2017
DOI: 10.1051/epjconf/201715804004

Probing the Anomalous Wtb couplings in different schemes of tWb associated production modeling

Alexey Baskakov[1,⋆], *Eduard* Boos[1,2,⋆⋆], *Viacheslav* Bunichev[1,⋆⋆⋆], *Georgi* Vorotnikov[1,⋆⋆⋆⋆], *Lev* Dudko[1,†], *Igor* Myagkov[1,‡], and *Maxim* Perfilov[1,§]

[1] *Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics (SINP MSU), 1(2), Leninskie gory, GSP-1, Moscow 119991, Russian Federation*
[2] *Faculty of Physics, Lomonosov Moscow State University, Leninskie Gory, Moscow 119991, Russian Federation*

Abstract. The impact of anomalous Wtb couplings on tWb process of the single top quark production has been tested in different schemes of tWb modeling. The scenario with right-handed vector operator (RV) in Wtb vertex with and without the presence of Standard model (SM) left-handed vector operator in Wtb vertex has been considered. It is shown that for anomalous Wtb couplings searches in tWb process usage of the full gauge invariant set of diagrams, with the same final state for the pair top quark production as well as for the single top quark production, is more justified than the usage of the schemes with deletion of some part of diagrams.

Introduction

There are three well-known processes of a single top quark production at hadron colliders, they are called s-channel, t-channel and tW-associated single top production [1]. All of them, except the last one, have been observed at Tevatron collider [2],[3],[4]. Due to its tiny cross section on the Tevatron collider tW-associated production have been observed at the LHC collider only recently [5]. While considering the tW-associated production it is necessary to take into account next-to-leading order corrections, specifically for the gluon splitting $g \to b\bar{b}$ which leads to the additional b-quark appearance in the final state, that is to say tWb processes. The main difficulty here is the identical final state of the double top quark production and the single top production so the interference between single top quark production Feynman diagrams and double top quark production ones appears.

The full process $pp \to t\bar{b}W^-$ contains subprocesses with two quarks or two gluons in the initial state and the last ones are dominant. In Fig. 1 all the diagrams of $gg \to t\bar{b}W^-$ subprocess for the tWb final state are listed.

⋆e-mail: a.baskakov@cern.ch
⋆⋆e-mail: Eduard.Boos@cern.ch
⋆⋆⋆e-mail: bunichev@theory.sinp.msu.ru
⋆⋆⋆⋆e-mail: georgii.vorotnikov@cern.ch
†e-mail: lev.dudko@cern.ch
‡e-mail: igor.myagkov@cern.ch
§e-mail: maksim.perfilov@cern.ch

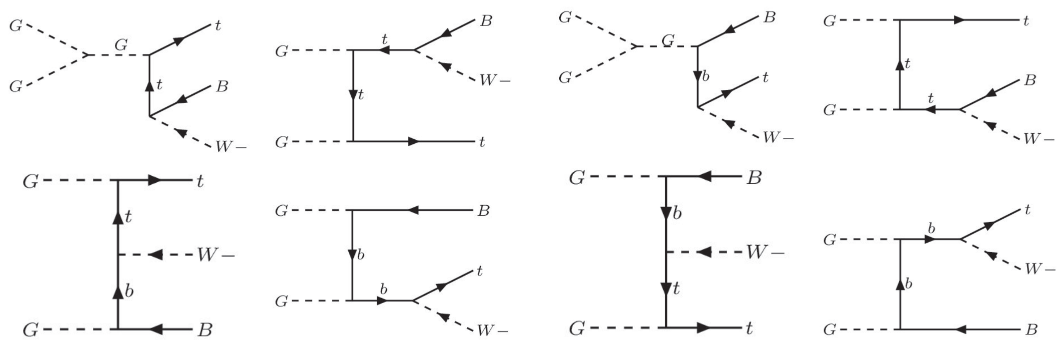

Figure 1: Diagrams for the process $gg \to t\bar{b}W^-$.

Let's consider the diagrams from Fig. 1 more circumstantially. The first, second and fourth diagrams from the top raw contain two top quarks in the final state with the subsequent decay of one of them - these are the diagrams of the double top production; other five diagrams correspond to the single top production. Different schemes of tWb modeling extract the single top production from the double top production in some or another way. E.g. in so-called *Diagram Removal* scheme [6],[7] all three double top production diagrams are removed and the other diagrams are considered. In this case the interference between double top and single top production diagrams has not taken into account. In a *Diagram Subtraction* scheme [7],[8] deletion of the double top production diagrams occurs after the squaring all the diagrams. In this case all the interference terms between double top and single top productions are kept, however this procedure leads to significant part of the simulated events with negative weights.

Among a very interesting physics tasks in the top quark sector, the searches for the anomalous operators in the Wtb vertex is one of the most promising ones due to direct impact of the anomalous operators to the cross sections and kinematic distributions of the single top quark production processes. There are direct searches for the anomalous operators in the t-channel single top production [9],[10],[11] however the same ones but in the tW-associated single top production have not been provided so far.

The aim of this paper is the study of the influence of the anomalous operators in the Wtb vertex on a different schemes of the tWb processes modeling. There is a short introduction to the anomalous Wtb operators formalism in Sec.1. In Sec.2 some distributions for different schemes of tWb processes modeling are shown for different contributions of the anomalous operators.

1 Anomalous structure of the Wtb vertex.

The most general, lowest dimension, CP conserving Lagrangian for the Wtb vertex has the following form [13, 14]:

$$\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_{\rm V}^{\rm L}P_{\rm L} + f_{\rm V}^{\rm R}P_{\rm R}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_{\rm W}}\left(f_{\rm T}^{\rm L}P_{\rm L} + f_{\rm T}^{\rm R}P_{\rm R}\right)t + h.c. \tag{1}$$

where $P_{\rm L,R} = \frac{1\mp\gamma_5}{2}$, $\sigma_{\mu\nu} = \frac{i}{2}(\gamma_{\mu}\gamma_{\nu} - \gamma_{\nu}\gamma_{\mu})$, form factor $f_{\rm V}^{\rm L}$ ($f_{\rm V}^{\rm R}$) represents the left-handed (right-handed) vector coupling, $f_{\rm T}^{\rm L}$ ($f_{\rm T}^{\rm R}$) represents the left-handed (right-handed) tensor coupling. The SM has the following set of coupling values: $f_{\rm V}^{\rm L} = V_{\rm tb}, f_{\rm V}^{\rm R} = f_{\rm T}^{\rm L} = f_{\rm T}^{\rm R} = 0$.

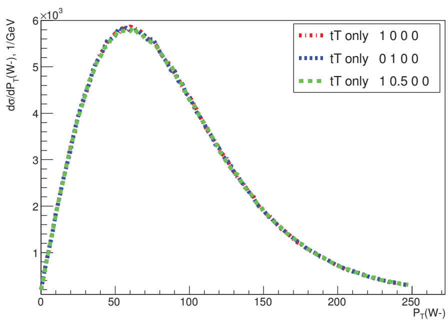

Figure 2: The distribution of the W-boson momenta for the top-pair production processes for different kinds of the *Wtb* vertex structure

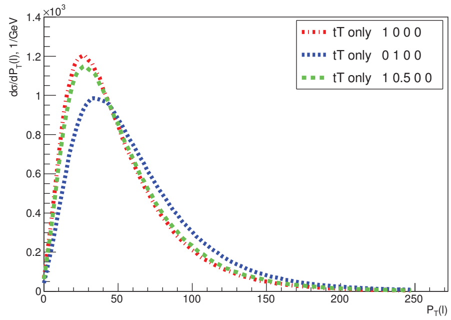

Figure 3: The distribution of the lepton from W-boson decay momenta for the top-pair production processes for different kinds of the *Wtb* vertex structure

At this paper the case with only vector operators are in the *Wtb* vertex (so called (f_V^L, f_V^R) scenario) is considered and all the notations have the form "f_V^L f_V^R 0 0".

2 The sensitivity of the different schemes of the *tWb* processes modeling to the presence of the anomalous right-handed vector operator in the *Wtb* vertex.

In this Sec. some kinematic distributions of the *tWb* process final state particles have been provided using the different subsets of the full diagram set of Fig. 1. The idea is to understand which scheme of the *tWb* processes modeling is the most correct to search for the anomalous couplings in the *Wtb* vertex. We tested the distribution of the transverse momenta of the W-boson of the process $gg \to t\bar{b}W^-$ (with 3 particles in the final state) and the transverse momenta of the lepton from the subsequent decay of the W-boson (4 particles in the final state, process $gg \to t\bar{b}l\bar{\nu}_l$).

The first, second and fourth diagram of the top raw from Fig. 1 correspond to the double top production. Of course the highlighting of these three diagrams with removing another ones is not the task of the *tWb* processes modeling, however in the pair top quark production processes all top quark decays through the *Wtb* vertex with 100% probability so they are more or less sensitive to the *Wtb* couplings. At the Fig 2 and Fig. 3 the transverse momentum of the W-boson from one of the top quarks decay and lepton from this W-boson decay are shown for the SM case (curve, labeled as "1 0 0 0"), the case with only right-handed vector operator is in the *Wtb* vertex only (curve, labeled as "0 1 0 0") and the case with the simultaneous presence of the SM part and the right-handed vector operator but with the value of its constant is equal to $f_V^R = 0.5$ (the curve "1 0.5 0 0") to show the situation with the SM and some contribution of new physics.

As it was mentioned earlier, pair top quark production has the top decay *Wtb* vertex only, that's the reason why the W-boson momentum distribution is (almost) not sensitive to the presence of the anomalous couplings in the *Wtb* vertex (all the curves completely coincide to each other). The presence of the additional part in the Lagrangian 1 leads to the enhancement of the production cross section. However, as it was mentioned in [12] the width of a top quark changes correspondingly. That's the reason why the shapes of all the curves from Fig 2 are similar to each other. Only the

 DOI: 10.1051/epjconf/201715804004

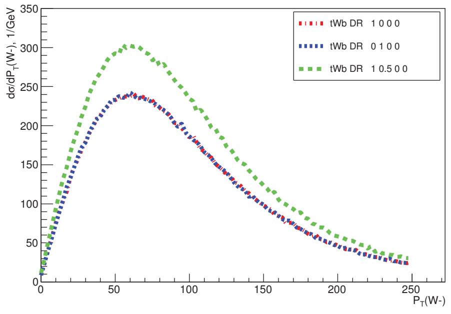

Figure 4: The distribution of the W-boson momenta for the Diagram Removal scheme of the tWb -processes modeling for different kinds of the Wtb vertex structure

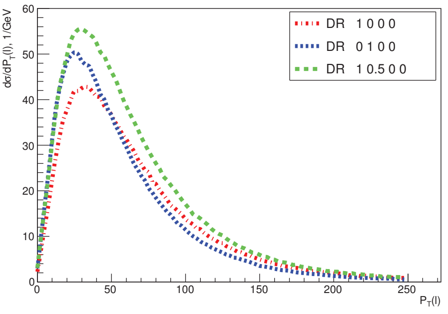

Figure 5: The distribution of the lepton from W-boson decay momenta for the Diagram Removal scheme of the tWb -processes modeling for different kinds of the Wtb vertex structure

lepton p_T distribution is sensitive to the anomalous right-handed vector operator due to the angular correlation of the top quark and its subsequent decay products.

One may expect the higher sensitivity to the anomalous couplings in the different schemes of tWb processes emphasizing due to the presence of two Wtb vertices in the single top quark production (and subsequent decays) in comparison to the double top quark production processes. At Fig. 4 and Fig. 5 the same distributions are shown but for the rest of the diagrams (3 diagrams from Fig.1, which correspond to the pair top quark production, have been deleted, other five are considered, this is *Diagram Removal* scheme of the tWb modeling).

W-boson p_T distribution for the "1 0 0 0" and "0 1 0 0" cases look exactly the similar to each other (due to the same cross section value in these cases; however the "1 0.5 0 0" curve differs from the another ones. It is explained by the cross section increment for $f_V^L = 1, f_V^R = 0.5$ values of couplings in comparison to the SM case ($f_V^L = 1$, other values of couplings are equal to zero). For the double top production the squared matrix element of the process has the top quark width in the denominator which leads to the same CS value for all three scenarios and the curve "1 0.5 0 0" coincides with the other two ones. It's not the case here, the squared matrix element of the diagrams for "Diagram Removal" scheme doesn't include the top quark width value, which leads to the cross section increment and the "1 0.5 0 0" curve places above the other two ones.

After squaring of all the diagrams from the Fig. 1 and deleting the six squared diagrams which are correspond to the double top production, the remaining squared diagrams will describe the single top production itself and the interference terms between double top and single top production, it is the *Diagram Subtraction* scheme of tWb processes modeling. One can expect almost the same sensitivity to the anomalous couplings in this case, that is shown in Figs. 6,7 where the chosen kinematic distributions are shown.

For the schemes considered above, the deletion of some of the diagrams from the complete set Fig.1 is needed. Specifically, using such kind of non-natural procedure leads to a violation of the gauge invariance (it results in the convergence of about 15% for the cross section of tWb process calculated in Feynman gauge beside the one calculated in unitary gauge for the *DiagramSubtraction* scheme.

The set of all diagrams from Fig. 1 is the full $tT + tWb$ process and represents itself the most gauge-invariant set of diagrams in comparison to the *Diagram Removal* and *Diagram Subtraction*

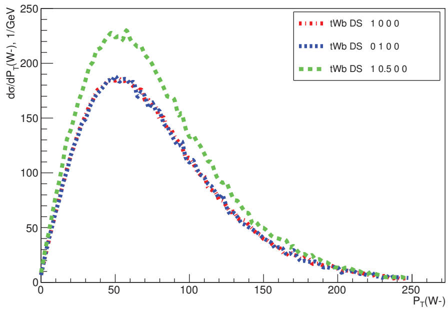

Figure 6: The distribution of the W-boson momenta for the Diagram Subtraction scheme of the tWb -processes modeling for different kinds of the Wtb vertex structure

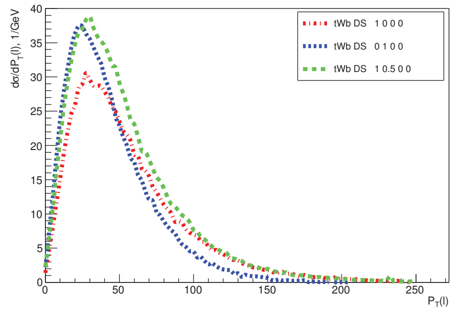

Figure 7: The distribution of the lepton from W-boson decay momenta for the Diagram Subtraction scheme of the tWb -processes modeling for different kinds of the Wtb vertex structure

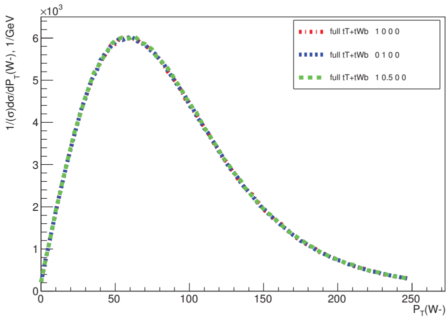

Figure 8: The distribution of the W-boson momenta for the full set of diagrams for different kinds of the Wtb vertex structure

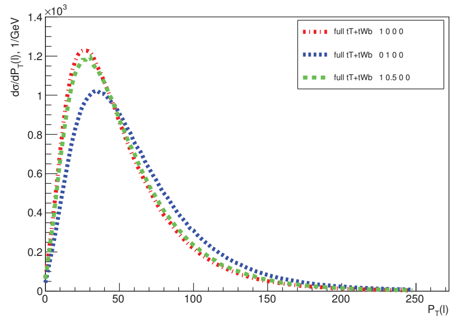

Figure 9: The distribution of the lepton from W-boson decay momenta for the full set of diagrams for different kinds of the Wtb vertex structure

schemes. The contribution of the pair top quark production diagrams is huge here, that's why the distributions from Fig. 8 and Fig. 9 look the same as for the double top production ones.

The sensitivity of the different subsets of the diagrams from the whole set of Fig. 1 is demonstrated on Figs. 10 and 11 for the case where right-handed operator only is presented in Wtb vertex with the value of its parameter is equal to $f_V^R = 1$ (other couplings are equal to 0). One can see here that different schemes have different sensitivity to anomalous operators.

Conclusion

The impact of the anomalous operators in Wtb vertex have been studied in different simulation schemes of tWb processes The special attention has been given to the correctness of the simulation and the sensitivity of the search for the anomalous right-handed vector operator in a Wtb vertex. As it was expected, manifestation of the anomalous contributions is more strong in the *Diagram Removal* and *Diagram Subtraction* simulation schemes in comparison to the full scheme which considers the

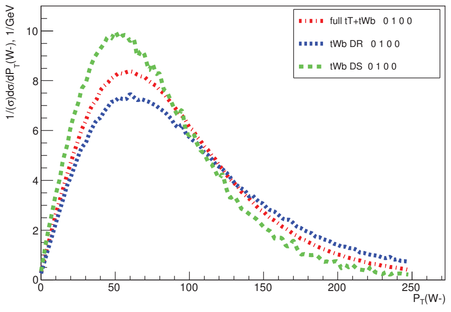

Figure 10: The distribution of the W-boson transverse momenta for the full set of diagrams, *tWb* Diagram Removal and *tWb* Diagram Subtraction schemes for the case when right-handed vector operator only is in the *Wtb* vertex. The curves are normalized to the corresponding cross sections.

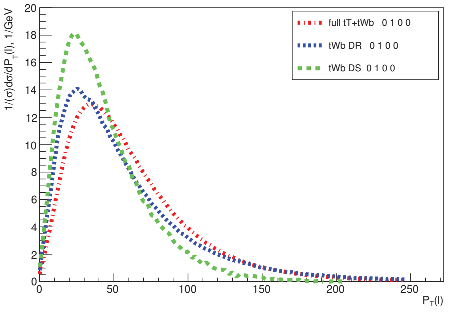

Figure 11: The distribution of the lepton from W-boson decay transverse momenta for the full set of diagrams, *tWb* Diagram Removal and *tWb* Diagram Subtraction schemes for the case when right-handed vector operator only is in the *Wtb* vertex. The curves are normalized to the corresponding cross sections.

complete set of the diagrams. Different behaviour is visible even for the distributions of the W-boson transverse momentum (without its decay) if the anomalous right-handed vector operator in the Wtb vertex turns on. However simulation of the complete set of tWb diagrams is preferable due to the usage of gauge invariant set of diagrams and correct simulation of all necessary properties. The similar sensitivity to the deviations in the couplings is demonstrated in the distributions of top quark decay products, like transverse momenta of a lepton which comes from W-boson decay and in angular variables.

References

[1] S. S. D. Willenbrock and D. A. Dicus, Phys. Rev. D **34**, 155 (1986). doi:10.1103/PhysRevD.34.155

[2] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **103**, 092001 (2009) doi:10.1103/PhysRevLett.103.092001 [arXiv:0903.0850 [hep-ex]].

[3] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 092002 (2009) doi:10.1103/PhysRevLett.103.092002 [arXiv:0903.0885 [hep-ex]].

[4] T. A. Aaltonen *et al.* [CDF and D0 Collaborations], Phys. Rev. Lett. **112**, 231803 (2014) doi:10.1103/PhysRevLett.112.231803 [arXiv:1402.5126 [hep-ex]].

[5] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **112**, no. 23, 231802 (2014) doi:10.1103/PhysRevLett.112.231802 [arXiv:1401.2942 [hep-ex]].

[6] A. S. Belyaev, E. E. Boos and L. V. Dudko, Phys. Rev. D **59**, 075001 (1999) doi:10.1103/PhysRevD.59.075001 [hep-ph/9806332].

[7] T. M. P. Tait, Phys. Rev. D **61**, 034001 (1999) doi:10.1103/PhysRevD.61.034001 [hep-ph/9909352].

[8] S. Frixione, E. Laenen, P. Motylinski, B. R. Webber and C. D. White, JHEP **0807**, 029 (2008) doi:10.1088/1126-6708/2008/07/029 [arXiv:0805.3067 [hep-ph]].

[9] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **101**, 221801 (2008) doi:10.1103/PhysRevLett.101.221801 [arXiv:0807.1692 [hep-ex]].
[10] V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **708**, 21 (2012) doi:10.1016/j.physletb.2012.01.014 [arXiv:1110.4592 [hep-ex]].
[11] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1702**, 028 (2017) doi:10.1007/JHEP02(2017)028 [arXiv:1610.03545 [hep-ex]].
[12] E. Boos, V. Bunichev, L. Dudko and M. Perfilov, Int. J. Mod. Phys. A **32**, no. 02n03, 1750008 (2016) doi:10.1142/S0217751X17500087 [arXiv:1607.00505 [hep-ph]].
[13] W. Buchmuller and D. Wyler, Nucl. Phys. B **268**, 621 (1986). doi:10.1016/0550-3213(86)90262-2
[14] G. L. Kane, G. A. Ladinsky and C. P. Yuan, Phys. Rev. D **45**, 124 (1992). doi:10.1103/PhysRevD.45.124