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Constraints on generalized non-standard tbW couplings

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General non-standard tbW couplings are studied as model independently as possible based on the effective Lagrangian consisting of the dimension-6 operators, which is an extension of the standard-model Lagrangian. The tbW-interaction Lagrangian in this framework includes four kinds of couplings, which could be complex. Constraints on those non-standard tbW couplings are obtained by comparing the experimental data related to the $t \to bW$ process with the corresponding theoretical formulas derived from the effective Lagrangian. The constraints on some sets of the non-standard couplings are shown not to be so strong because those couplings balance out each other as we treat all the non-standard couplings as complex numbers at the same time.

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The top quark, discovered more than 20 years ago, is regarded as one of the most attractive particles for new-physics searches even now because of its huge mass. Therefore, top-quark physics is one of the main topics at the High-Luminosity Large Hadron Collider (HL-LHC) and the International Linear Collider (ILC) as well as the current Large Hadron Collider (LHC). In particular, various measurements of the top quark will be performed more precisely at the HL-LHC and the ILC as new-physics searches. At the experiments the purpose of which is precision measurements, deviations from the standard-model predictions are probed as signals of new physics. However, it is not easy to specify the model for the new physics from the beginning since such deviations could be induced via quantum effects of new particles in many other models as well. Thus, model-independent analyses would be an important key to building new-physics models beyond the standard model as a bottom-up approach. In this proceedings, we report the constraints on the most general non-standard tbW couplings in the effective Lagrangian based on our two recent studies [1, 2].

In order to construct the effective Lagrangian, we assume the masses of non-standard particles are much heavier than the cut-off scale Λ. In this case, the effective Lagrangian is written as

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i \left[C_i O_i + C_i^* O_i^\dagger\right], \tag{1}$$

where $\mathscr{L}_{\rm SM}$ is the standard-model Lagrangian, O_i are the dimension-6 operators and their unknown coefficients C_i, combined with Λ^{-2}, produce the non-standard coupling constants. The $t \to bW$ process we focus on could be affected by the following operators [3, 4];

$$O^{(3,33)}_{\phi q} = i\sum_I [\phi^\dagger(x)\tau^I D_\mu \phi(x)][\bar{q}_{L3}(x)\gamma^\mu \tau^I q_{L3}(x)] \tag{2}$$

$$O^{33}_{\phi\phi} = i[\tilde{\phi}^\dagger(x) D_\mu \phi(x)][\bar{u}_{R3}(x)\gamma^\mu d_{R3}(x)] \tag{3}$$

$$O^{33}_{uW} = \sum_I \bar{q}_{L3}(x)\sigma^{\mu\nu}\tau^I u_{R3}(x)\tilde{\phi}(x) W^I_{\mu\nu}(x) \tag{4}$$

$$O^{33}_{dW} = \sum_I \bar{q}_{L3}(x)\sigma^{\mu\nu}\tau^I d_{R3}(x)\phi(x) W^I_{\mu\nu}(x), \tag{5}$$

where the notations obey basically those in Ref.[3]. Using these operators, we derive the effective tbW Lagrangian as

$$\begin{aligned}\mathscr{L}_{tbW} = -\frac{g}{\sqrt{2}}\Big[&\bar{\psi}_b(x)\gamma^\mu (f_1^L P_L + f_1^R P_R)\psi_t(x) W^-_\mu(x) \\ &+ \bar{\psi}_b(x)\frac{\sigma^{\mu\nu}}{M_W}(f_2^L P_L + f_2^R P_R)\psi_t(x)\partial_\mu W^-_\nu(x)\Big],\end{aligned} \tag{6}$$

where g is the $SU(2)$ coupling constant, $P_{L/R} \equiv (1 \mp \gamma_5)/2$,

$$f_1^L \equiv V_{tb} + C^{(3,33)*}_{\phi q}\frac{v^2}{\Lambda^2}, \qquad f_1^R \equiv C^{33*}_{\phi\phi}\frac{v^2}{2\Lambda^2},$$
$$f_2^L \equiv -\sqrt{2}C^{33*}_{dW}\frac{v^2}{\Lambda^2}, \qquad f_2^R \equiv -\sqrt{2}C^{33}_{uW}\frac{v^2}{\Lambda^2},$$

with v being the Higgs vacuum expectation value and V_{tb} being the (tb) element of Kobayashi-Maskawa matrix. We then decompose f_1^L into the standard and non-standard model parts: $f_1^L = f_{\rm SM}^1 + \delta f_1^L$, and set as $f_{\rm SM}^1 = V_{tb} = 1$ and $\delta f_1^L \equiv C^{(3,33)*}_{\phi q} v^2/\Lambda^2$ hereafter.

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Although studies of the tbW couplings using the effective Lagrangian have already been performed in order to probe possible new interactions [♯1], it is assumed there that the non-standard couplings are real numbers, or partially complex numbers, and/or only some couplings have been treated as free parameters at once fixing the others. In addition, it has not been unusual to adopt the linear approximation in those parameters, i.e., to neglect their quadratic (and higher-power) terms. However, in this analysis, we give the constraints on non-standard tbW couplings treating all those couplings as complex numbers (i.e., an eight-parameter analysis is carried out) without the above-mentioned assumption and approximation.

In our numerical analysis, the following experimental information is used as our input data:

- the total decay width of the top quark [8]

$$\Gamma^t = 1.36 \pm 0.02(\text{stat.})^{+0.14}_{-0.11}(\text{syst.})\ \text{GeV.}^{\sharp 2} \tag{7}$$

- the partial decay widths derived from experimental data of W-boson helicity fractions [9]

$$\begin{aligned} \Gamma_L^{t*} &= 0.439 \pm 0.051\ \text{GeV}, \\ \Gamma_0^{t*} &= 0.926 \pm 0.103\ \text{GeV}, \\ \Gamma_R^{t*} &= -0.005 \pm 0.020\ \text{GeV}. \end{aligned} \tag{8}$$

Varying all the non-standard couplings at the same time, we have compared the above experimental data with the corresponding theoretical formulas derived from the effective Lagrangian, and explored allowed areas for each parameter. The resultant constraints on the eight parameters are shown in Table 1. In addition, since it might seem strange that the contribution from the standard-model coupling f_{SM}^1 is diminished by its extended coupling δf_L^1 as can be seen in Table1, the constraints on the other couplings in the case of Re(δf_1^L) = 0 and Re(δf_1^L) = Im(δf_1^L) = 0 are also derived and shown in Tables 2 and 3.

Table 1: Allowed maximum and minimum values of the non-standard-top-decay couplings in the case that all the couplings are dealt with as free parameters.

	δf_1^L		f_1^R		f_2^L		f_2^R	
	Re(δf_1^L)	Im(δf_1^L)	Re(f_1^R)	Im(f_1^R)	Re(f_2^L)	Im(f_2^L)	Re(f_2^R)	Im(f_2^R)
Min.	−2.58	−1.58	−1.36	−1.36	−0.68	−0.68	−1.20	−1.20
Max.	0.58	1.58	1.36	1.36	0.68	0.68	1.20	1.20

Table 2: Allowed maximum and minimum values of non-standard-top-decay couplings in the case that all the couplings are dealt with as free parameters except for Re(δf_1^L) being set to be zero.

	δf_1^L	f_1^R		f_2^L		f_2^R	
	Im(δf_1^L)	Re(f_1^R)	Im(f_1^R)	Re(f_2^L)	Im(f_2^L)	Re(f_2^R)	Im(f_2^R)
Min.	−1.23	−1.14	−1.12	−0.55	−0.57	−0.96	−1.00
Max.	1.23	1.10	1.12	0.59	0.57	0.00	1.00

[♯1] The preceding works are listed in [1, 2], and here we add Refs. [5, 6, 7] to the lists.

[♯2] In fact, it is not easy to handle an asymmetric error like this in the error propagation, we use $\Gamma^t = 1.36 \pm 0.02(\text{stat.}) \pm 0.14(\text{syst.})$ GeV, the one symmetrized by adopting the larger (i.e., $+0.14$) in this systematic error.

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Table 3: Allowed maximum and minimum values of non-standard-top-decay couplings in the case that all the couplings are dealt with as free parameters except for $\mathrm{Re}(\delta f_1^L)$ and $\mathrm{Im}(\delta f_1^L)$ both being set to be zero.

	f_1^R		f_2^L		f_2^R	
	$\mathrm{Re}(f_1^R)$	$\mathrm{Im}(f_1^R)$	$\mathrm{Re}(f_2^L)$	$\mathrm{Im}(f_2^L)$	$\mathrm{Re}(f_2^R)$	$\mathrm{Im}(f_2^R)$
Min.	-1.14	-1.12	-0.55	-0.57	-0.96	-0.49
Max.	1.10	1.12	0.59	0.57	0.00	0.49

In summary, the maximum and minimum values of the non-standard *tbW* couplings allowed by the present experimental data of the top-quark total and partial decay widths were derived by varying all the couplings independently at the same time. We found that

- In the case that all the coupling constants are treated as complex numbers, the allowed regions of those couplings are not that small yet because cancellations could happen among the contributions originated from those couplings.
- If we assume that f_1^L does not include any non-standard contribution, the resultant constraints on the other non-standard couplings, especially f_2^R, become a bit stronger, although their allowed ranges are not such tiny that we can drop their quadratic terms safely.

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