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New physics contributions to Wtb anomalous couplings and top-quark decay

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In this work, we study the new physics effects arising due the presence of anomalous Wtb vertex through the semileptonic decay modes of the top-quark at the Large Hadron Collider. An estimate on the sensitivities of the aforementioned interaction at 5σ CL in the context of top-quark decay-width measurements and cross-section measurements would also be discussed for the pre-existing 13 TeV LHC data and its projections for the proposed LHC runs at 14 TeV, 27 TeV and 100 TeV. We also incorporate the CP-violating effects to such interactions by constructing the CP-violating asymmetries.

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1. Introduction

The charge parity (CP)-violation phenomenon that was first observed in neutral-kaon decay [1] needs to be explored beyond the Standard-Model (SM) as SM only provides a small amount of CP-violation via the CKM-matrices [2] which is not sufficient to explain the matter-antimatter asymmetry of the Universe [3]. The aim of this present article is to investigate the CP-violating effects of the anomalous Wtb vertex and provide stringent constraints on anomalous Wtb couplings using the measurements of top-quark decay width and cross-section as well as production asymmetries. Anomalous interactions in top-quark production and decay have been widely explored in the previous literature [4].

We consider an effective field theory approach to parameterise the anomalous Wtb vertex. In this framework, the most general Wtb vertex is expressed as [5]:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\left[\gamma^{\mu}\left(C_{1L}P_L + C_{1R}P_R\right)W_{\mu}^{-} - i\sigma^{\mu\nu}\left(\tilde{C}_{2L}P_L + \tilde{C}_{2R}P_R\right)\left(\partial_{\nu}W_{\mu}^{-}\right)\right]t + h.c., \tag{1}$$

Where C_{1L}, C_{1R}, $\tilde{C}_{2L}$ ($\frac{C_{2L}}{\Lambda}$) and $\tilde{C}_{2R}$ ($\frac{C_{2R}}{\Lambda}$) are dimensionless complex anomalous couplings, $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$ and Λ is the energy scale. In SM at tree level $C_{1L} = V_{tb} = 1$ and other couplings are zero.

2. Numerical Analysis

We begin the analysis by incorporating the Lagrangian given in Eq. 1 into `Feynrules` [6], which then interfaced with `Feyncalc` [7] for further simulations. The decay level CP-asymmetries will be defined as:

$$\mathcal{A}^{\Gamma}_{SM} = \frac{\Delta\Gamma_{t\to bW}}{\Gamma_{t\to bW}} \simeq \frac{\mathrm{Im}\left(|\mathcal{M}|^2_{t\to bW}\right)}{\mathrm{Re}\left(|\mathcal{M}|^2_{t\to bW}\right)} \tag{2}$$

where $|\mathcal{M}|^2_{t\to bW}$ is the matrix-element squared for the process of top (anti-top) decay into b ($\bar{b}$)-quark and W^+ (W^-)-boson. The expression for the relative decay width of the top-quark with anomalous coupling to the SM decay width is:

$$R^{\Gamma} = \frac{\Gamma_{t\to bW}}{\Gamma^{SM}_{t\to bW}} = 1 - \frac{M_W}{(1+2\eta^2)}[6\eta C_R - M_W(\eta^2+2)(C_L^2 + C_R^2)] \tag{3}$$

where $\eta = \frac{M_W}{m_t}$, $C_L = |C_L|e^{i\theta}$ and $C_R = |C_R|e^{i\phi}$.

In Fig. 1, we show the dependence of the relative change in decay width and cross-section, $\frac{\Delta\sigma}{\sigma}$ on moduli of the anomalous coupling at different values of phases θ and ϕ. We observe that the decay width as well as cross-section is more sensitive to coupling C_R and the contribution from the coupling C_L is negligible. In Table 1, we present the constraints on anomalous couplings C_L and C_R at 2.5σ C.L. (when only one anomalous coupling is taken non zero at a time) obtained from the top-quark decay width measurements.

	C_L ($\times 10^{-3}$)	C_R ($\times 10^{-3}$)
$\left(\frac{\Delta\Gamma}{\Gamma}\right)_{t\to bW}$	$-5.86 \leq C_L \leq 5.86$	$-1.84 \leq C_R \leq 1.95$
$\left(\frac{\Delta\sigma}{\sigma}\right)^{13TeV}_{pp\to t\bar{t}}$	$-2.62 \leq C_L \leq 2.62$	$-0.40 \leq C_R \leq 0.40$

Table 1: Bounds on anomalous couplings C_L (when $C_R = 0$) and C_R (when $C_L = 0$) at 2.5σ C.L. obtained from measurements of top-quark decay width and top-pair production cross-section at the LHC with $\sqrt{s} = 13$ TeV.

In the same way as the decay width, the production asymmetries could be estimated using the formula,

$$\mathcal{A}^{\sigma}_{SM} = \frac{\Delta\sigma_{pp\to t(\to bW^+)\bar{t}(\to\bar{b}W^-)}}{\sigma_{pp\to t(\to bW^+)\bar{t}(\to\bar{b}W^-)}} \simeq \left(\frac{\mathrm{Im}\left(|\mathcal{M}|^2_{t\to bW}\right)}{\mathrm{Re}\left(|\mathcal{M}|^2_{t\to bW}\right)}\right)^2. \tag{4}$$

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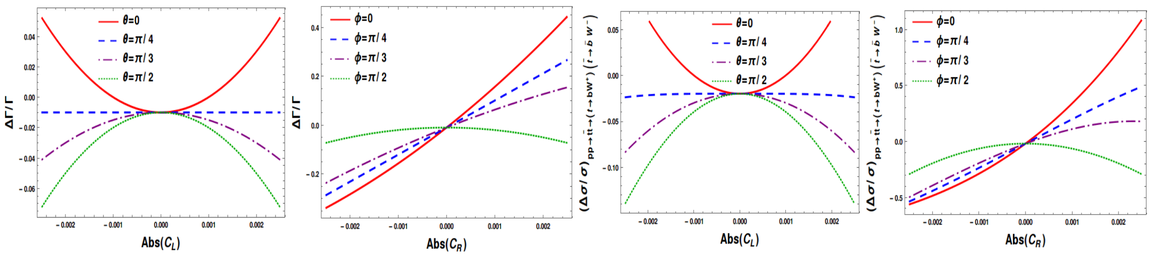

Figure 1: Dependence of decay width of top-quark and cross-section on the moduli of anomalous couplings for different values of θ and ϕ for the cases with $|C_R| = 0$ and $|C_L| = 0$.

Fig. 2 presents the 1σ, 2.5σ and 5σ regions in Abs(C_L)-Arg(C_L) plane and Abs(C_R)-Arg(C_R) plane allowed by the production asymmetries at LHC with $\sqrt{s}$ = 13 TeV, HL-LHC with $\sqrt{s}$ = 14 TeV, HE-LHC with $\sqrt{s}$ = 27 TeV and FCC-hh with $\sqrt{s}$ =100 TeV. It should be noted that an approximate prediction of the constraints on the phase and moduli of the anomalous couplings C_L and C_R at 2.5σ C.L. can be given from Fig. 2, however an exact calculation has been carried out to obtain the limits and the values obtained are presented in Table 2.

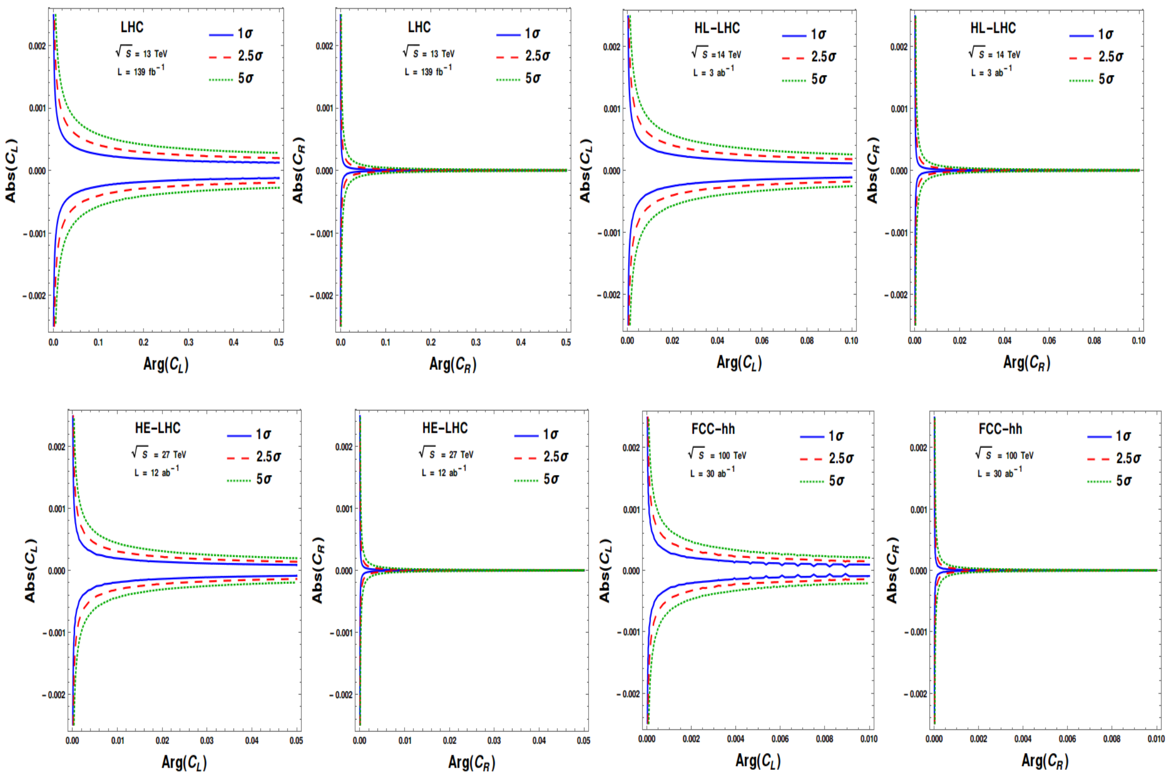

Figure 2: 1σ, 2.5σ and 5σ C.L. regions in the Abs(C_L)-Arg(C_L) plane and Abs(C_R)-Arg(C_R) plane allowed by the production asymmetry at LHC with $\sqrt{s}$ = 13 TeV, HL-LHC with $\sqrt{s}$ = 14 TeV, HE-LHC with $\sqrt{s}$ = 27 TeV and FCC-hh with $\sqrt{s}$ = 100 TeV.

3. Conclusions

In this study, we have explored the CP-violating effects of the anomalous Wtb vertex in the context of top-quark via its decay into a b-quark and a W-boson. An estimate of the constraints on the anomalous couplings C_L and C_R have been presented using top-quark decay width and cross-section measurements as well as production asymmetries. The values of the limits obtained on the couplings C_L and C_R are presented in Tables 1 and 2.

Collider	$\sqrt{s}$, $\int Ldt$	$\lvert C_L\rvert$ ($\times 10^{-4}$)	$\lvert C_R\rvert$ ($\times 10^{-4}$)
LHC	13 TeV, 139 fb^{-1}	1.82	0.03
HL-LHC	14 TeV, 3.0 ab^{-1}	0.81	0.006
HE-LHC	27 TeV, 12.0 ab^{-1}	0.44	0.0017
FCC-hh	100 TeV, 30.0 ab^{-1}	0.21	0.0004

Table 2: Bounds on the moduli of the anomalous couplings C_L (when $C_R = 0$) and C_R (when $C_L = 0$) for CP-violating phase, $\theta = \phi = \frac{\pi}{4}$ at 2.5σ C.L. obtained from production asymmetries at LHC, HL-LHC, HE-LHC and FCC-hh.

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