

CP -violating anomalous interactions at Large Hadron Collider

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In this study, we explore the effects of CP -violating anomalous interactions of the top-quark through the semileptonic decay modes of the top-quark arising due to pair-production of $t\bar{t}$ at the Large Hadron Collider. Predictions on the LHC sensitivities of the coupling strength to such CP -violating interactions would be discussed for the 13 TeV LHC data and for the future hadron collider with 14 TeV energy.

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1. Introduction

The Standard-Model (SM) is known as the most complete and rich model that is capable of explaining a large number of experimental data. Despite this, SM is incomplete as it is unable to explain some phenomena such as $\mathcal{CP}$ -violation [1, 2], neutrino mass [3, 4], existence of dark matter and dark energy [5] etc. This indicates that there should be extensions to the SM to answer these open questions that cannot be addressed by SM. In the present article, we explore the possibility to search for $\mathcal{CP}$ -violation in the process of top-quark pair production via proton-proton collision in the semi-leptonic decay modes of the top (anti-top)-quark. In particular, we find the $\mathcal{CP}$ -violation sensitivity to anomalous top-quark couplings using T-odd triple product correlations [6, 7] constructed through the momenta of the end state particles for the already present data at LHC with $\sqrt{S} = 13$ TeV and its luminosity intense variant HL-LHC with $\sqrt{S} = 14$ TeV. $\mathcal{CP}$ -violating anomalous top-quark interactions have been studied extensively in the existing literature [8–13].

We consider the model independent approach where the $\mathcal{CP}$ -violation in the top-pair production vertex is parameterised by anomalous top-quark coupling. The SM Lagrangian could be modified through following effective Lagrangian where the modification in the top-pair production vertex occurs through the additional term in the Lagrangian [11]:

$$\mathcal{L}_{int} = -i \frac{g_s}{2} \left(\frac{d_g}{\Lambda} \right) \bar{t} \sigma_{\mu\nu} \gamma_5 G^{\mu\nu} t, \quad (1)$$

where g_s is the strong coupling constant, $G^{\mu\nu}$ is the gluon field-strength tensor, d_g is the interaction strength and Λ is the $\mathcal{CP}$ -violation energy scale. We consider the following T-odd correlations induced by the anomalous top-quark couplings in the process $pp \rightarrow t\bar{t} \rightarrow (bl^+\nu_l)(\bar{b}l^-\bar{\nu}_l)$ [14].

$$\begin{aligned} \mathcal{C}_1 &= \epsilon(p_b, p_{\bar{b}}, p_{l^+}, p_{l^-}), \\ \mathcal{C}_2 &= \tilde{q} \cdot (p_{l^+} - p_{l^-}) \epsilon(p_{l^+}, p_{l^-}, p_b + p_{\bar{b}}, \tilde{q}), \\ \mathcal{C}_3 &= \tilde{q} \cdot (p_{l^+} - p_{l^-}) \epsilon(p_b, p_{\bar{b}}, p_{l^+} + p_{l^-}, \tilde{q}), \\ \mathcal{C}_4 &= \epsilon(P, p_b - p_{\bar{b}}, p_{l^+}, p_{l^-}), \\ \mathcal{C}_5 &= \epsilon(p_b + p_{l^+}, p_{\bar{b}} + p_{l^-}, p_b + p_{\bar{b}}, p_{l^+} - p_{l^-}), \end{aligned} \quad (2)$$

where $\epsilon(a, b, c, d)$ is defined as $\epsilon(a, b, c, d) = \epsilon_{\mu\nu\alpha\beta} a^\mu b^\nu c^\alpha d^\beta$ with $\epsilon_{0123} = 1$, which is a completely anti-symmetric tensor and represents the Levi-Civita symbol of rank 4, p_b ($p_{\bar{b}}$) represents the momenta of the b ($\bar{b}$)-quark and p_{l^+} (p_{l^-}) represents the momenta of the lepton(anti-lepton) that emerges from W^+ (W^-) boson. P and $\tilde{q}$ are the sum and difference of the two initial proton beams which can be numerically defined as

$$P = p_b + p_{l^+} + p_{\bar{b}} + p_{l^-}, \quad \tilde{q} = P_1 - P_2. \quad (3)$$

All observables defined in equation 2 are odd under $\mathcal{CP}$ -transformation and take the form of triple product $\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$, where p_i ($i=1,2,3$) represents the momentum vectors.

2. Numerical Analysis

We begin the simulation by incorporating the Lagrangian given in Eq. 1 in the **FeynRules** [15], which then interfaced with the **Madgraph5** [16] for the event generation of $t\bar{t}$ pair via the process $pp \rightarrow t\bar{t}$ at LO. The events produced were then interfaced with **pythia8** [17] for shower and Hadronisation. The values of the SM input parameters used in our study are given in Table 1, the value of renormalisation and factorisation scale is taken to be M_Z and the parton distribution functions (PDF) considered was nn23lo1. We perform the analysis for LHC with $\sqrt{S} = 13$ TeV for the integrated luminosity of 36.1 fb^{-1} and 140 fb^{-1} and High Luminosity LHC HL-LHC with $\sqrt{S} = 14$ TeV for the projected luminosities of 0.3 ab^{-1} and 3 ab^{-1} . The following cuts are implemented for generating the events:

$$P_T(l^\pm) > 20 \text{ GeV}, P_T(b, \bar{b}) > 25 \text{ GeV}, \eta(b, \bar{b}, l^\pm) < 2.5, \\ \Delta R(b\bar{b}) > 0.4, \Delta R(l^+l^-) > 0.2, \Delta R(bl) > 0.4, \cancel{E}_T > 30 \text{ GeV}. \quad (4)$$

SM parameter	Experimental value
$m_b(m_b)$	$4.7 \pm 0.06 \text{ GeV}$
$m_t(m_t)$	$173.0 \pm 0.4 \text{ GeV}$
M_W	$80.387 \pm 0.02 \text{ GeV}$
$\alpha_s^{\overline{MS}}(M_Z)$	0.118 ± 0.001

Table 1: Standard Model input parameter values [18].

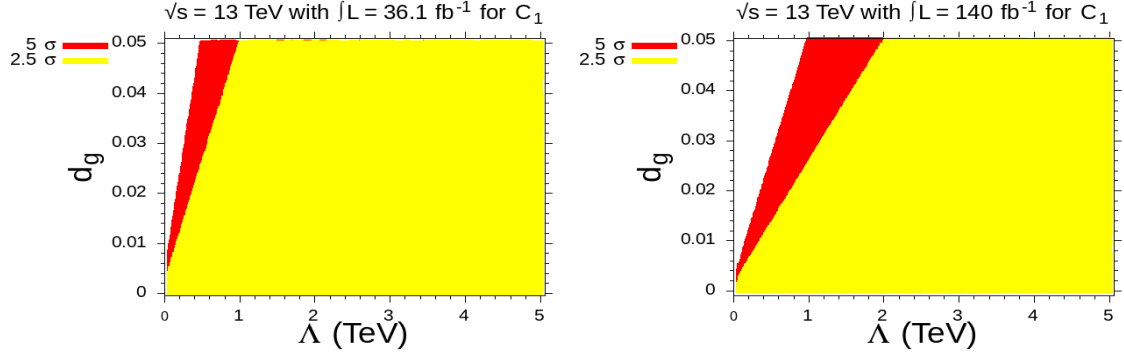


Figure 1: The 2.5σ (yellow) and 5σ (red) regions in d_g - Λ plane allowed by the production asymmetries in the semileptonic decay modes at LHC with $\sqrt{S} = 13$ TeV for the integrated luminosities of 36.1 fb^{-1} (left) and 140 fb^{-1} (right) respectively.

We use the method of finding asymmetries to study $\mathcal{CP}$ -violation. A non-zero value of asymmetry would indicate the presence of $\mathcal{CP}$ -violation. For this, we first produce events for the process concerned for different sets of values of the coupling constant and the $\mathcal{CP}$ -violation scale (d_g, Λ). The obtained results were then used for further analysis. In Figs. 1

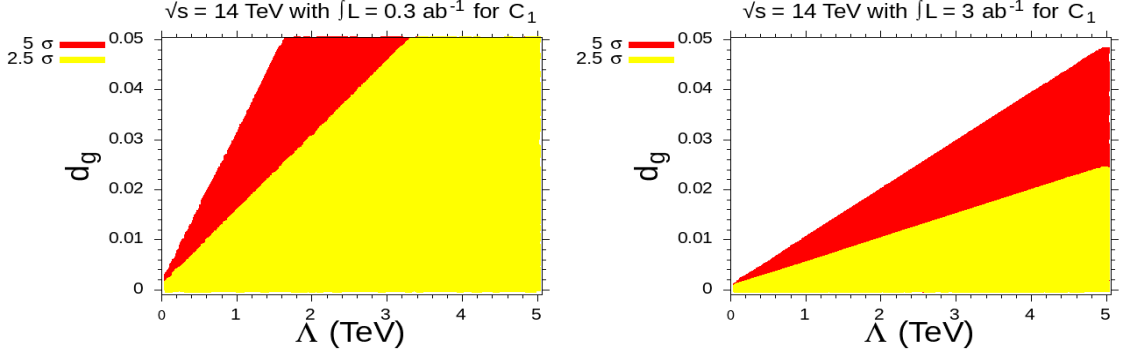


Figure 2: The 2.5σ (yellow) and 5σ (red) regions in d_g - Λ plane allowed by the production asymmetries in the semileptonic decay modes at HL-LHC with $\sqrt{S} = 14$ TeV for the integrated luminosities of 0.3 ab^{-1} (left) and 3 ab^{-1} (right) respectively.

and 2, we show the 2.5σ CL and 5σ CL regions in d_g - Λ plane allowed by the production asymmetries in the semileptonic decay modes at LHC with $\sqrt{S} = 13$ TeV for the integrated luminosities of 36.1 fb^{-1} and 140 fb^{-1} and at HL-LHC with $\sqrt{S} = 14$ TeV for the integrated luminosities of 0.3 ab^{-1} and 3 ab^{-1} . As we can see in the Figs. 1 and 2, we have a wide set of (d_g, Λ) values to achieve 5σ sensitivity for $\mathcal{CP}$ -violating anomalous top-quark coupling. The bounds on the coupling $\tilde{d}_g$ at LHC with $\sqrt{s} = 13$ TeV and HL-LHC with $\sqrt{S} = 14$ TeV for the luminosities of 36.1 fb^{-1} to 3 ab^{-1} are given in Table 2.

3. Conclusions

We have explored $\mathcal{CP}$ -violating anomalous couplings in the top-pair production vertex through the process $pp \rightarrow t\bar{t} \rightarrow (bl^+\nu_l)(\bar{b}l^-\bar{\nu}_l)$. In particular, we find constraints on $\mathcal{CP}$ -violating anomalous top couplings by measurement of production asymmetry in the semileptonic detection modes. The sensitivity to $\mathcal{CP}$ -violating coupling at 2.5σ CL and 5σ CL for LHC with $\sqrt{S} = 13$ TeV and HL-LHC with $\sqrt{S} = 14$ TeV for luminosities of 36.1 fb^{-1} , 140 fb^{-1} and 0.3 ab^{-1} , 3 ab^{-1} , respectively are presented in Table 2.

$\sqrt{S}$ (TeV)	$\int \mathcal{L} dt$	$\left \frac{\tilde{d}_g}{\Lambda} \right $ (in GeV^{-1})	
		at 3σ C.L.	at 5σ C.L.
13	36.1 fb^{-1}	0.29×10^{-4}	0.6×10^{-4}
	140 fb^{-1}	0.52×10^{-5}	0.2×10^{-4}
14 (HL-LHC)	0.3 ab^{-1}	0.39×10^{-5}	0.6×10^{-5}
	3.0 ab^{-1}	0.14×10^{-4}	0.1×10^{-4}

Table 2: bounds on coupling $\tilde{d}_g$ $\left(\left| \frac{\tilde{d}_g}{\Lambda} \right| \right)$ at 3σ CL and 5σ CL in the context of top-pair production through the process $pp \rightarrow t\bar{t} \rightarrow (bl^+\nu_l)(\bar{b}l^-\bar{\nu}_l)$ at LHC with $\sqrt{S} = 13$ TeV and HL-LHC with $\sqrt{S} = 14$ TeV for the luminosities of 36.1 fb^{-1} , 140 fb^{-1} and 0.3 ab^{-1} , 3 ab^{-1} , respectively.

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