T-ODD GLUON–TOP-QUARK COUPLINGS AT LHC

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Abstract

The T–odd top–quark chromoelectric dipole moment, $d_t$, is probed through top–quark–pair production via gluon fusion at the CERN LHC with the possibility of having polarized proton beams in account. At 1-σ level, the typical CP-odd lepton energy and tensor correlations enable us to measure $Re(d_t)$ and $Im(d_t)$ up to the order of $10^{-18}$ (g$_s$cm) in the unpolarized case and the initial CP-odd gluon spin correlation allows us to probe $Im(d_t)$ up to the order of $10^{-20}$ (g$_s$cm) for $\sqrt{s} = 14$ TeV and the integrated luminosity $L_{pp} = 10$ fb$^{-1}$.

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Top quark is expected to be sensitive to new physics at TeV energy scale, not readily observable in lighter quarks, and it is copiously produced at proton-proton collisions at LHC, predominantly through gluon–gluon fusion. Therefore, we probe the possibility of measuring the $T$-odd basic coupling of gluon and top quark, top-quark chromoelectric dipole moment ($tCEDM$) at LHC [1].

The process $gg \rightarrow t\bar{t}$, followed by $t$ and $\bar{t}$ semileptonic decays, has been studied to extract the real part of the $T$-odd $tCEDM$ form factor by using the optimal observables [2]. We extend the work to measuring the imaginary part of $tCEDM$ and extract the real and imaginary parts through typical $CP$-odd lepton and antilepton correlations [3] in the $t$ and $\bar{t}$ semileptonic decays.

It has been demonstrated [4] that the $CP$ properties of the Higgs boson can be directly probed with the initial $CP$-odd spin correlations of gluons, whose polarization is from polarized proton beams. We apply the initial gluon-gluon spin correlations to measuring the imaginary part of the $tCEDM$ and compare them with the $CP$-odd lepton correlations from the $t$ and $\bar{t}$ semileptonic decays.

In general the gluon–top–quark interaction Lagrangian consist of two Standard Model(SM) dimension-four terms and two dimension-five terms:

$$\mathcal{L}_M = \frac{1}{2} g_s \left( \frac{c_t}{2m_t} \right) i\sigma^{\mu\nu} G_{\mu\nu}^a T_a t, \quad \mathcal{L}_E = \frac{i}{2} g_s \left( \frac{\tilde{c}_t}{2m_t} \right) i\sigma^{\mu\nu} \gamma_5 G_{\mu\nu}^a T_a t, \quad (1)$$

where $\sigma^{\mu\nu} = \frac{i}{2} [\gamma^{\mu}, \gamma^\nu]$, $G_{\mu\nu}^a$ is the gluon field strength, and $T_a = \frac{1}{2} \lambda_a$ ($a = 1$ to 8). Among the four terms, only the $\mathcal{L}_E$ violates $T$ invariance and defines the $tCEDM$ $d_t \equiv g_s(\tilde{c}_t/2m_t)$. In the SM, this $tCEDM$ form factor is extremely small [3] because it arises only at three or more loops. On the other hand, the $tCEDM$ can be much larger in many models of $CP$ violation such as the multi-Higgs-doublet models and Minimal Supersymmetric Standard Model [3]. In this light, a nonvanishing $tCEDM$ should be a strong indication of new physics beyond the SM.

Firstly, let us consider the case that proton beams are unpolarized. In this case the initial unpolarized gluon-gluon system in the process $gg \rightarrow t\bar{t}$ is $CP$ invariant and therefore any detection of the $tCEDM$ requires information on the final $t\bar{t}$ spin correlations. The spin correlations can be indirectly inferred through the lepton and antilepton correlations of the semileptonic top and antitop quark decays $t \rightarrow bl^+\nu_l$ and $\bar{t} \rightarrow bl^-\bar{\nu}_l$ ($l = e, \mu$). We may employ two typical $CP$-odd and $CP\bar{T}$-even correlations [3]

$$A_1 = \hat{p}_g \cdot (\vec{p}_l \times \vec{p}_\bar{\nu}), \quad T_{33} = 2(\vec{p}_l - \vec{p}_\bar{\nu})_3(\vec{p}_l \times \vec{p}_\bar{\nu})_3, \quad (2)$$
Table 1: Attainable 1-σ limits on $Re(d_t)$ and $Im(d_t)$, through $T_{33}$, $A_E$ and $Q_{33}$ for the parameter set (4).

| observable | Attainable 1-σ limits |
|------------|----------------------|
| $T_{33}$   | $|Re(d_t)| = 0.899 \times 10^{-17} g_s cm$ |
| $A_E$      | $|Im(d_t)| = 0.858 \times 10^{-18} g_s cm$ |
| $Q_{33}$   | $|Im(d_t)| = 0.205 \times 10^{-17} g_s cm$ |

and three $CP$-odd and $CPT$-odd correlations

$$A_E = E_i - E_l, \quad A_2 = \vec{p}_g \cdot (\vec{p}_l + \vec{p}_{\bar{l}}),$$

$$Q_{33}^l = 2(\vec{p}_l + \vec{p}_{\bar{l}})_3(\vec{p}_l - \vec{p}_{\bar{l}})_3 - \frac{2}{3}(\vec{p}_l^2 - \vec{p}_{\bar{l}}^2).$$ (3)

However, Bose symmetry of the initial $gg$ system forces the vector correlations $A_1$ and $A_2$ to vanish so that no information on the $t$CEDM can be extracted from them. So, we should use $T_{33}$ as a $CPT$-even correlation, which is proportional to the real part of the $t$CEDM, and $A_E$ and $Q_{33}$ as $CPT$-odd correlations, which is proportional to the imaginary part of the $t$CEDM.

In our numerical analysis we use the following experimental parameters:

$$\epsilon = 10\%, \quad B_l = B_{\bar{l}} = 21\% \quad \text{for} \quad l = e, \mu,$$

$$\sqrt{s} = 14 \text{ TeV}, \quad L_{pp} = 10 \text{ fb}^{-1}, \quad m_t = 175 \text{ GeV},$$ (4)

where $\epsilon$ stands for a detection efficiency. For the unpolarized gluon distribution function, we employ the GRVHO parametrization [7]. Table 1 shows the 1-σ sensitivities of the $CP$-odd correlations, $T_{33}$, $A_E$ and $Q_{33}$ to $Re(d_t)$ and $Im(d_t)$, respectively, for the parameter set (4). Quantitatively, $T_{33}$ and $Q_{33}$ enable us to probe $Re(d_t)$ and $Im(d_t)$ of the order of $10^{-17} g_s cm$, respectively, and $A_E$ allows us to probe $Im(d_t)$ down to the order of $10^{-18} g_s cm$.

Secondly, let us consider the case that proton beams are polarized. It has been claimed in many works [8] that gluons in a polarized proton should be polarized to explain the observed EMC effect. We assume in this work that the polarization transmission from protons to gluons exist and use the gluon polarization to form a $CP$-odd gluon-gluon spin correlation to measure the $t$CEDM. This initial $CP$-odd configuration allows us to consider all the detectable $t\bar{t}$ decay modes without any full reconstruction of the decay products. One of the simplest $CP$-odd
asymmetries is the rate asymmetry:

$$A \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-},$$

which has been used to probe the $CP$ properties of the Higgs boson $H$. Here, $\sigma_{\pm}$ is the cross section of $t\bar{t}$ production in collision of an unpolarized proton and a proton of helicity $\pm$. It is straightforward to check that the difference and sum of the two cross sections for opposite proton helicities are given by

$$d\sigma_+ - d\sigma_- \sim g_1 \Delta g_2 Im(c_t), \quad d\sigma_+ + d\sigma_- \sim g_1 g_2,$$

where $g_1(g_2)$ is the helicity-summed gluon distribution function inside the unpolarized (polarized) proton, $g_{1,2} = g_{1,2}^+ + g_{1,2}^-$, and $\Delta g_2 = g_{2,2}^+ - g_{2,2}^-$, where $\pm$ is for gluon helicity.

The sensitivity of the $CP$-odd rate asymmetry to $Im(d_t)$ is crucially dependent on the degree of gluon polarization achievable for polarized protons at the CERN LHC. At present the function $\Delta g(x) = g_+ - g_-(x)$ indicating the degree of gluon polarization in a polarized proton is not precisely known except for the fact that it should satisfy the asymptotic boundary conditions: $\Delta g(x)/g(x) \to 1$ for $x \to 1$ and $\Delta g(x)/g(x) \propto x$ for $x \to 0$. Several models, which satisfy these constraints, suggest that a significant amount of the proton spin is carried by gluons. In our numerical analysis we employ the BQ parametrization $\Delta g$ as an example of $\Delta g$.

Table 2 shows the number of $t\bar{t}$ events, $N$, and the 1-$\sigma$ limits of $|Im(d_t)|$ for an integrated luminosity of 10 fb$^{-1}$. Note that there is no drastic $p_T$-cut dependence. This feature can be used to make a large $p_T$ cut to reduce large background effects without spoiling the sensitivities of the rate asymmetry to the $t$CEDM. Remarkably, $Im(d_t)$ are much more strongly constrained by the rate asymmetry than the lepton and antilepton energy correlation $A_E$ (See Table 1.).
Numerically, it is possible to measure $Im(d_t)$ up to the order of $10^{-20}$ g·cm at 1-$\sigma$ level, although precise limits require more precise theoretical estimates and experimental determinations of the polarized gluon distribution.

To summarize, we can measure (i) the real and imaginary parts of the $T$-odd $t$CEDM up to the order of $10^{-18}$ g·cm by the $CP$-odd lepton energy and tensor correlations of the $t$ and $\bar{t}$ semileptonic decays in unpolarized proton-proton collisions, and (ii) the imaginary part of the $t$CEDM up to the order of $10^{-20}$ g·cm through the production rate asymmetry for positively versus negatively polarized protons, assuming that the polarization transmission from the proton to gluons exists. Certainly, the large enhancement obtained by use of proton polarization is worthwhile to be checked at the CERN LHC.

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