Vol. 7 (2014) *Acta Physica Polonica B Proceedings Supplement* No 3

PROBING ANOMALOUS TOP QUARK COUPLINGS IN DIFFRACTIVE EVENTS AT THE LHC*

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(Received May 26, 2014)

We investigated the impact of anomalous chromomagnetic and chromoelectric dipole moments on the top pair production in diffractive events at the LHC. The exclusive diffractive production of top quarks provides clean environment due to having one proton intact. We found that the effect of these corrections is remarkable in $pp \to p\gamma p \to pt\bar{t}X$ processes.

DOI:10.5506/APhysPolBSupp.7.579
PACS numbers: 14.65.Ha, 12.60.–i, 14.70.Dj

1. Introduction

At low energies, the Standard Model (SM) is a reliable theory to describe the experimental results in particle physics studies up to now. However, from the phenomenological point of view, one may attempt to model the effects of high energy interactions of the possible nonstandard particles on the experimental observables at the LHC, with the effective Lagrangian approach containing modified interaction terms.

Amongst the SM fundamental particles, top quark is the heaviest one with a mass $m_t \simeq 175$ GeV close to the electroweak symmetry breaking energy scale, and this is the reason why the top couplings are more sensitive to the new physics. Many works have discussed the top quark nonstandard interactions, for example the top-charged Higgs boson ones [1] and the CP violating couplings among this quark and different gauge fields in the top pair production or decay processes at Tevatron as well as the LHC [2].

The violation of CP symmetry in the SM emerges from a complex phase in the CKM matrix. This asymmetry, even in the top quark decay processes, is too small to explain the matter–antimatter asymmetry in the universe and

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[*] Presented at "Excited QCD 2014", Bjelašnica Mountain, Sarajevo, Bosnia and Herzegovina, February 2–8, 2014.

the weak interaction properties in particle physics. Therefore, the measurement of large amounts of CP violation in the top quark events can be an evidence of Beyond SM physics. The electric dipole moment of top quark which is achieved through three-loop level perturbations in SM is described as a new source of CP violation [3]. Motivated by the structure of this dipole moment, we can modify the top-gauge field vertices with the CP violating anomalous form factors, to investigate the nonstandard effects in the top production processes.

At this point, we concentrate on a proton–proton diffractive collision with the center-of-mass energy $\sqrt{s} = 14$ TeV. Here, the emitted photon from the first proton can interact with the second one without the presence of proton remnants. Some of the ATLAS and CMS collaborations plans are aimed to understand such processes that are classified as the forward physics studies. The mediated interaction, γp, in deep inelastic scattering, leads to the top pair production in the final state $t\bar{t}X$. It is clear that the cross section measurement of the whole proton–proton scattering which includes the direct impacts of anomalous couplings of top quarks is remarkable, especially in the diffractive collisions. These events are clean since one of the protons remains intact, losing only a small fraction of its initial energy.

In the present paper, we start by introducing an effective Lagrangian for a top pair production process that comprises the modified interactions and then continue with the cross section calculations for a diffractive collision at the LHC. Later, we will show that the simultaneous anomalous couplings of both kind of gauge fields, increases the cross section to the values more than the ones expected from the case with just the gluons anomalous interactions.

2. The effective Lagrangian

The top quark interaction with the electromagnetic fields and the gluons may be proposed in a gauge invariant effective Lagrangian with model-independent couplings as

$$\mathcal{L}_{\text{int}} = -g_e Q_t \bar{\psi}_t \mathit{\Gamma}_e^\mu \psi_t A_\mu - g_s \bar{\psi}_t \frac{\lambda^a}{2} \mathit{\Gamma}_c^\mu \psi_t G_\mu^a \,, \tag{1}$$

where g_e, g_s are $\mathrm{U(1)_{em}}$ and $\mathrm{SU(3)_c}$ coupling constants respectively, $\sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$ and λ^a are $\mathrm{SU(3)_c}$ color matrices. Generally, the quantum corrections to the fundamental quark-gauge field vertices are known in the form of some anomalous terms which can be simplified by appealing to some of the SM symmetries, like Lorentz invariance. Similarly, we may define the $\mathit{\Gamma}_{c/e}^\mu$ matrices as

$$\mathit{\Gamma}_{c/e}^\mu = \gamma^\mu + \frac{i}{2m_t}\left(\hat{a}_{c/e}^V + i\hat{a}_{c/e}^A \gamma^5\right)\sigma^{\mu\nu}\ell_\nu \,. \tag{2}$$

Here, $\hat{a}_e^V$ and $\hat{a}_e^A$ stand for the anomalous magnetic and electric form factors respectively, while $\hat{a}_c^V$ ($\hat{a}_c^A$) is the anomalous chromo-magnetic (chromo-electric) form factor. Moreover, ℓ_ν represents the four momenta of gauge fields A_μ and G_μ^a. Inserting (2) into (1), we arrive at the anomalous terms with constant coefficients proportional to the corresponding dipole moments and the whole Lagrangian only contains the operators with the mass dimensions $d \leq 6$. In this notation, the matrix $\gamma^5\sigma^{\mu\nu}\ell_\nu$ parameterizes a new source of CP violating interactions, if any, in the top pair productions at the LHC.

2.1. Scattering amplitudes

The t-channel and u-channel tree level diagrams of the sub-process $g\gamma \to t\bar{t}$ has different amplitudes in terms of top quark spinors and the polarization vectors of gauge fields as

$$\begin{aligned} M_t^{a,\mu\nu} &= \bar{u}(p_1)\left(-ig_s\frac{\lambda^a}{2}\mathit{\Gamma}_c^\mu\right)(\gamma.q+m_t)(-ig_e\mathit{\Gamma}_e^\nu)v(p_2)\varepsilon_\mu(k_1)\varepsilon_\nu(k_2)\,, \\ M_u^{a,\mu\nu} &= \bar{u}(p_1)(-ig_e\mathit{\Gamma}_e^\mu)\left(\gamma.q'+m_t\right)\left(-ig_s\frac{\lambda^a}{2}\mathit{\Gamma}_c^\nu\right)v(p_2)\varepsilon_\mu(k_2)\varepsilon_\nu(k_1)\,, \end{aligned} \quad (3)$$

where p_i and k_i with $i = 1, 2$ are the momenta of the final top quarks and the initial gauge fields respectively. Moreover, $t = q^2 = (p_1 - k_1)^2 = (k_2 - p_2)^2$, $u = q'^2 = (k_1 - p_2)^2 = (p_1 - k_2)^2$. The diagrams contributing to this scattering are shown in Fig.1. In [4], the authors considered this sub-process with the top-gluons anomalous couplings and computed the cross section of a diffractive collision at the LHC. Here, our aim is to generalize the above work to the case where the anomalous couplings are included for both the photon and gluons interactions simultaneously, with the definition of relation (2). Finally, we will compare our results for the cross section with the ones in [4]. The allowed regions of our four parameters will be presented in a future publication.

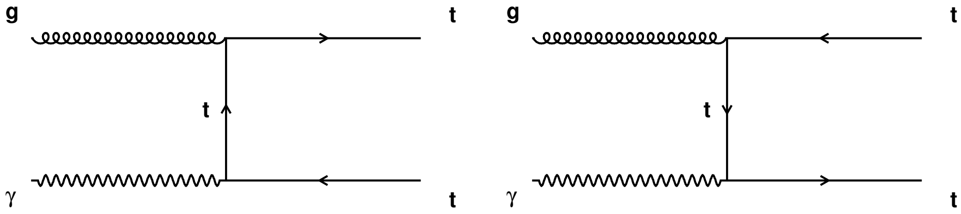

Fig. 1. t-channel and u-channel tree level diagrams of the sub-process $g\gamma \to t\bar{t}$.

2.2. Equivalent photon approximation

In leading order, high energy electrons scattering from a nucleon are connected to nucleon by one photon propagator. The photon carrying momentum $q^2 \sim -4EE' \sin^2\theta/2$, while E and E' are the energies of incoming and outgoing electrons respectively. In the context of forward scattering, we have $q^2 = 0$, consequently the virtual photon turns into a real photon. This quasi-real photon with virtuality Q^2 and energy E_γ is described by equivalent photon approximation [5–7]

$$\frac{dN_\gamma}{dE_\gamma dQ^2} = \frac{\alpha}{\pi}\frac{1}{E_\gamma Q^2}\left[\left(1-\frac{E_\gamma}{E_p}\right)\left(1-\frac{Q^2_{\min}}{Q^2}\right)F_E + \frac{E^2_\gamma}{2E^2_p}F_M\right] . \tag{4}$$

Here, E_p is the initial energy of the proton. The minimum photon virtuality is available from $Q^2_{\min} = \frac{m_p^2 E_\gamma^2}{E_p(E_p-E_\gamma)}$, where m_p is the proton mass.

For elastic processes, the electric and magnetic proton form factors depend only on the four momentum transfer. Both of them are well approximated by a dipole fit [8]

$$\begin{aligned} F_E &= \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2}\,, & F_M &= G_M^2\,, \\ G_E^2 &= \frac{G_M^2}{\mu_p^2} = \left(1+\frac{Q^2}{0.71}\right)^{-4} = G_D^2\,, & \mu_p^2 &= 7.78\,. \end{aligned} \tag{5}$$

At inelastic processes

$$F_E = \int dx F_2/x\,, \qquad F_M = \int dx F_2/x^3\,. \tag{6}$$

F_2 is the proton structure function which is integrated over Bjorken scaling variable x.

3. Sensitivity of cross section to anomalous dipole moments

The cross section of the $t\bar{t}$ production from process $pp \to p\gamma p \to pt\bar{t}X$ can be obtained by integrating the parton level cross section for the subprocess $g\gamma \to t\bar{t}$ over the photon spectra and the gluon distribution function

$$\sigma_{(pp\to p\ t\bar{t}X)} = \int dQ^2\ dx_1\ dx_2 \left(\frac{dN_\gamma}{dx_1 dQ^2}\right)\left(\frac{dN_g}{dx_2}\right)\hat{\sigma}_{(g\gamma\to t\bar{t})} . \tag{7}$$

The parameters x_1 and x_2 are the proton's momentum fractions carried by the photon and a gluon, respectively. Q^2 is the factorization scale. $\frac{dN_g}{dx_2}$ is the gluon distribution function of the proton. Here, we used the parton distribution functions extracted by MSTW [9].

The differentials $dx_1\, dx_2$ can be changed into $dz\, dx_1$ to help us evaluate integrals. Where $z = \sqrt{x_1 x_2} \simeq \sqrt{\frac{\hat{s}}{s}}$, the Jacobian of this transformation is $2z/x_1$

$$\sigma_{(pp \to p\ t\bar{t}X)} = \int_{Q^2_{\text{min}}}^{Q^2_{\text{max}}} dQ^2 \int_{z_{\text{min}}}^{z_{\text{max}}} dz\ 2z \int_{x_{1_{\text{min}}}}^{x_{1_{\text{max}}}} \frac{dx_1}{x_1} \left(\frac{dN_\gamma}{dx_1 dQ^2} \right) N_q(z^2/x_1)\ \hat{\sigma}_{(g\gamma \to t\bar{t})}\,. \quad (8)$$

Upper and lower bounds of integrals are considered as $z_{\text{min}} = \frac{M_{\text{inv}}}{\sqrt{s}}$, $z_{\text{max}} = \sqrt{\xi_{\text{max}}}$, $x_{1_{\text{min}}} = \text{MAX}(z^2,\ \xi_{\text{min}})$, $x_{1_{\text{max}}} = \xi_{\text{max}}$. M_{inv} is the total mass of the final top quarks.

As demonstrated in Eq. (5), the electric and magnetic proton form factors fall rapidly with the increase of Q^2. Consequently, changing the value of Q^2_{max} creates negligible uncertainty. We take $Q^2_{\text{max}} = 2$ GeV^2. Larger values do not have any considerable effect on the above cross section. We consider the fractional proton energy loss region of $0.0015 < \zeta < 0.5$. This interval provides the most sensitive region to the anomalous couplings [4].

In Figs. 2 and 3, the sensitivity of the total cross section, $\sigma \equiv \sigma(\hat{a}_e^A, \hat{a}_e^V, \hat{a}_c^A, \hat{a}_c^V)$, to its anomalous couplings is illustrated. Indeed, the ratio $(\sigma - \sigma_{\text{SM}})/\sigma_{\text{SM}}$ is shown in terms of each parameter. As we can prove from the amplitudes in relation (3), the impacts of the photon couplings and the gluons ones are the same. This means that to have a complete estimate of CP violation through the cross section calculations with the concentration on quark-gauge fields interactions, we must consider all of the anomalous couplings. This is because the mentioned gauge fields, no matter what kind of local symmetries is included, have equal contributions in the scattering processes.

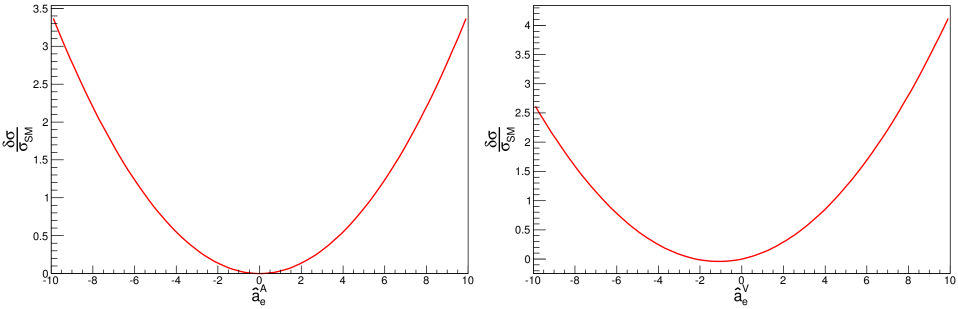

Fig. 2. The sensitivity of the total cross section of process $p\gamma p \to pt\bar{t}X$ to the anomalous couplings $\hat{a}_e^A$ (left panel) and $\hat{a}_e^V$ (right panel).

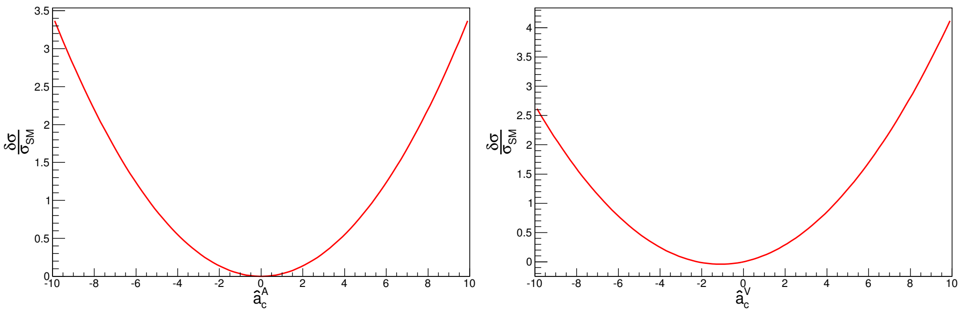

Fig. 3. The sensitivity of the total cross section of process $p\gamma p \rightarrow pt\bar{t}X$ to the anomalous couplings $\hat{a}_c^A$ (left panel) and $\hat{a}_c^V$ (right panel).

The authors would like to thank M. Mohammadi Najafabadi for valuable discussions.

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