Top quark electric and magnetic color dipole moments in a Two Higgs Doublet Model with CP violation

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Abstract.
In this work we study the anomalous top quark-gluon couplings Chromoelectric Dipole Moment and Chromomagnetic Dipole Moment in a general THDM with CP violation also known as THDM Type III. We include the contribution to the color electric and magnetic couplings arising from the $Y_{tt}$ Yukawa coupling. We provide phenomenological restrictions to chromoelectric and chromomagnetic anomalous couplings within the model.

1. Introduction
The top quark is one of the most interesting fermions in the Standard Model (SM), it is the heaviest one with a mass close to the electroweak symmetry breaking scale. There is now in operation the largest machine ever built, fortunately the Large Hadron Collider (LHC) happens to be the place where most top quark pairs are produced allowing the study of top quark properties and providing an optimal site to measure its couplings to the gauge fields and to perform searches for new physics. Top quark Chromomagnetic dipole moment (CMDM) is induced at one loop level in the SM and chromoelectric dipole moment (CEDM) appears from the complex CKM phase only at three loop level [1]. In extended models with new sources of CP violation the study of new physics from anomalous couplings becomes important. CMDM and CEDM are defined through the effective Lagrangian

$$\mathcal{L} = \bar{u}(t) \frac{-g_s}{2m_t} G_{\mu\nu} T^a \left( \Delta\tilde{\kappa} + i\gamma_5 \Delta\tilde{d} \right) u(t),$$

the real part of the anomalous coupling $\Delta\tilde{\kappa}$ is the CMDM and in the imaginary part appears $\Delta\tilde{d}$ the CEDM, $G_{\mu\nu}$ is the gluon field strength, and $T^a$ are the QCD fundamental generators of SU(3)$_c$ [2].

Recently, the CMS collaboration reported the following bound $Re(\Delta\tilde{\kappa}) = 0.037 \pm 0.041$, at 95%CL [3]. Also from Tevatron and Atlas results on the cross section $m_{t\bar{t}}$ there are reported limits to CMDM and CEDM, $|\Delta\tilde{\kappa}| < 0.05$ and $\Delta\tilde{d} < 0.16$ at 95%C.L. [4]. Within uncertainties still in agreement with the SM prediction to the CMDM, which is $\Delta\tilde{\kappa} \sim 5.6 \times 10^{-2}$ [5]. In the
near future with increased integrated luminosity and energy the experimental bound to CEDM expected to be improved up to $\Delta \theta < 0.05$ [4].

In this work we study the THDM Type-III \(^1\) contribution in the quark top CMDM and CEDM [2]. This kind of model explicitly violates the CP symmetry in the scalar potential, and the top quark CMDM is generated at one loop level.

2. The general two Higgs doublet model

The scalar potential for the general two Higgs doublet model is

$$V = -\mu_1^2 \Phi_1^+ \Phi_1 - \mu_2^2 \Phi_2^+ \Phi_2 - \left[ \mu_{12}^2 \Phi_1^+ \Phi_2^+ + h.c. \right]$$

$$+ \left( \frac{1}{2} \lambda_1 \left( \Phi_1^+ \Phi_1 \right)^2 + \frac{1}{2} \lambda_2 \left( \Phi_2^+ \Phi_2 \right)^2 + \lambda_3 \left( \Phi_1^+ \Phi_1 \right) \left( \Phi_2^+ \Phi_2 \right) + \lambda_4 \left( \Phi_1^+ \Phi_2 \right) \left( \Phi_2^+ \Phi_1 \right) \right)$$

where $\mu_1^2$, $\mu_2^2$, $\lambda_1$, $\lambda_2$, $\lambda_3$ and $\lambda_4$ are real parameters and $\mu_{12}^2$, $\lambda_5$, $\lambda_6$, and $\lambda_7$ could have complex values allowing explicit CP violation. The neutral components in the fields are defined as $\frac{1}{\sqrt{2}}(\eta_1 + \eta_2 + i\chi_1)$ and $\frac{1}{\sqrt{2}}(\eta_2 - \eta_1 - i\chi_2)$. The vacuum expectation values (VEV) can be taken real because complex phases can be reabsorbed by the complex parameters of scalar potential.

Due to the explicit CP symmetry breaking, there is mixing among the CP-odd and CP-even scalar sectors. Defining $\tan \beta = \frac{\eta_2}{\eta_1}$, we take the scalar field $(\eta_3 = -\chi_1 s_\beta + \chi_2 c_\beta)$ orthogonal to the Would-be Goldstone component corresponding to the Z gauge boson. After symmetry breaking, the mass eigenstates of the neutral Higgs bosons are related to the CP mixed $\eta_j$ states as

$$h_i = \sum_{j=1}^{3} R_{ij} \eta_j,$$  \hspace{1cm} (3)

where $i = 1, 2, 3$ and the $R$ matrix is given by [6, 7];

$$R = \begin{pmatrix}
c_1 c_2 & s_1 c_2 & s_2 \\
-c_1 s_2 s_3 + s_1 c_3 & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\
-c_1 s_2 c_3 + s_1 s_3 & -c_1 s_3 + c_1 s_2 c_3 & c_2 c_3
\end{pmatrix},$$ \hspace{1cm} (4)

with $c_i = \cos \alpha_i$ and $s_i = \sin \alpha_i$, with $i = 1, 2, 3$. The eigenstates $h_i$ are not CP pure states and their mixing is given by the R matrix. Note that in the limit case $s_2 = s_3 = 0$ the case of THDM without CP violation is recovered.

The Yukawa Lagrangian for the quark sector has the general form

$$-\mathcal{L}_{\text{Yukawa}} = \sum_{i,j=1}^{3} \sum_{a=1}^{2} \left( \bar{q}^0_{La} Y^{0 \mu}_{ajj} \Phi^{0 \mu}_a + \Phi^{\dagger \mu}_{La} Y^{\mu \nu \mu \nu}_{ajj} \Phi^{\nu \nu}_a d^0_R + h.c. \right).$$ \hspace{1cm} (5)

In the above equation, $Y^{u,d,\nu}_{a}$ are the $3 \times 3$ Yukawa matrices. $q_L$ denotes the left handed quark doublets and $u_R$, $d_R$, represent the right handed quark singlets under $SU(2)_L$. The mass matrix after spontaneous symmetry breaking is

$$M^{u,d} = \sum_{a=1}^{2} \frac{v_a}{\sqrt{2}} Y^{u,d}_{a},$$ \hspace{1cm} (6)

\(^1\) The Mexican high energy physics community has been very productive in the study of models beyond the SM with an extended scalar sector. See for instance talk contributions by J. Barranco, A. Bolaños, L. Díaz-Cruz, Montes de Oca, J. Orduz and D. Rojas, just to mention a few.
\[ Y^f_a = V^f_L V^0^f_a (V^f_R)^\dagger, \] for \( f = u, d, \) and \( V^f_{L,R} \) are the rotation matrices that diagonalize the mass matrix. The Yukawa matrix \( Y^a \) as a function of \( M^u \) and \( Y^a \) gives THDM-II Lagrangian, with tree level flavor changing. For the up sector the Yukawa Lagrangian can be written as

\[ -\mathcal{L}_Y = \frac{1}{\sin \beta} \sum_{ijk} \bar{u}_i M^u_{ij} (A^u_k P_L + A^{*u}_k P_R) u_j h_k \]

\[ + \frac{1}{\sin \beta} \sum_{ijk} \bar{u}_i Y^u_{ij} (B^u_k P_L + B^{*u}_k P_R) u_j h_k, \]

(7)

where

\[ A^u_k = R_{k2} - i R_{k3} \cos \beta, \]
\[ B^u_k = R_{k1} \sin \beta - R_{k2} \cos \beta + i R_{k3}. \]

(8)

The \( Y_{ij} \) also gives a contribution to the anomalous couplings CEDM and CMDM of the same order of the one in the THDM-II coming from \( (\bar{u}_i M^u_{ij} (A^u_k P_L + A^{*u}_k P_R) u_j h_k). \)

Figure 1. Feynman Diagram for the anomalous quark-gluon couplings in the general THDM.

3. CMDM and CEDM in the general THDM

We will take into account three contributions in the model to the total CMDM and CEDM. (1) The anomalous couplings contributions arising from the diagram in Figure (1) from now on will be denoted as \( \Delta \tilde{\kappa} \) and \( \Delta \tilde{d}_t \), (2) the contribution from the Yukawa coupling \( Y_{ij} \) denoted as \( \Delta \tilde{\kappa}_{tt} \) and \( \Delta \tilde{d}_{tt} \), and finally (3) contributions from the coupling proportional to \( M^u \) in one vertex and \( Y^u \) in the other vertex also known as an interference term \( \Delta \tilde{\kappa}_{int} \) and \( \Delta \tilde{d}_{int} \).

To obtain the analytic expressions for the above mentioned loop integrals we apply the method presented in [8, 9, 10]. Anomalous couplings will be dependent on \( A^u_k \) and \( B^u_k \) in Eq. 8, linear combinations of the \( \alpha_{1,2,3} \) mixing angles and \( \tan \beta \), they will also be dependent on the masses of the Higgses \( h_1, h_2, \) and \( h_3 \). For simplicity we will take the hierarchical arrangement where \( h_1 \) is the SM Higgs, and \( m_{h_2} = m_{h_3} = m_{H^+} \). In this partially degenerate case there is CP violation for \( \alpha_2 \neq 0 \) [11]. We denote the three contributions as \( \Delta \tilde{\kappa}_t = \Delta \tilde{\kappa} + \Delta \tilde{\kappa}_{tt} + \Delta \tilde{\kappa}_{int} \) and \( \Delta \tilde{d}_t = \Delta \tilde{d} + \Delta \tilde{d}_{tt} + \Delta \tilde{d}_{int} \). Explicit expressions can be found in [2].

In Figure 2 we show the scatter plot in the \( \Delta \tilde{\kappa}_t \) and \( \Delta \tilde{d}_t \) plane with random values of the mixing angles \( \alpha_1, \alpha_2 \) and \( \alpha_3 \) for a set of fixed values of \( \tan \beta \). In Figure 3 and Figure 4 also the mixing angle \( \alpha_3 \) is fixed to \( \alpha_3 = 0 \) and \( \alpha_3 = \pi/4 \) respectively. The masses of the heavier Higgses in this case are \( m_{h_2} = m_{h_3} = m_{H^+} = 500 \text{ GeV} \).
Figure 2. Scatter plot in the $\Delta\tilde{\kappa}_t$ and $\Delta\tilde{d}_t$ plane with random values of the mixing angles $\alpha_1, \alpha_2$ and $\alpha_3$, for the specified values of $\tan \beta = 1$, 1.5, 2, 5, 10.

Figure 3. Scatter plot in the $\Delta\tilde{\kappa}_t$ and $\Delta\tilde{d}_t$ plane with random values of the mixing angles $\alpha_1, \alpha_2$ and $\alpha_3 = 0$, for the specified values of $\tan \beta = 1$, 1.5, 2, 5, 10.

4. Results in the restricted parameter space
We will study nine regions of interest in the $\alpha_1$-$\alpha_2$ parameter space, this approximate regions are described in Table 1 and are those already under consideration in [12]. The allowed regions
Figure 4. Scatter plot in the $\Delta \tilde{\kappa}_t$ and $\Delta \tilde{d}_t$ plane with random values of the mixing angles $\alpha_1, \alpha_2$ and $\alpha_3 = \pi/4$, for the specified values of $\tan \beta = 1, 1.5, 2, 5, 10$.

Table 1. Definition of the phenomenologically allowed regions under study, we specify the values of $M_{H^\pm}$ and $\tan \beta$ in each region [2]. In all cases $\alpha_3 = 0$.

| Region | $\alpha_1$ (GeV) | $\alpha_2$ (GeV) | $M_{H^\pm}$ (GeV) | $\tan \beta$ |
|--------|------------------|------------------|-------------------|-------------|
| $R_1$  | $0.67 \leq \alpha_1 \leq 0.8$ | $0 \leq \alpha_2 \leq 0.23$ | 300 | 1 |
| $R_2$  | $0.8 \leq \alpha_1 \leq 1.14$ | $-0.25 \leq \alpha_2 \leq 0$ | 300 | 1 |
| $R_3$  | $1.18 \leq \alpha_1 \leq 1.55$ | $-0.51 \leq \alpha_2 \leq 0$ | 500 | 1 |
| $R_4$  | $-1.57 \leq \alpha_1 \leq -1.3$ | $-0.46 \leq \alpha_2 \leq 0$ | 350 | 1.5 |
| $R_5$  | $0.93 \leq \alpha_1 \leq 1.57$ | $-0.61 \leq \alpha_2 \leq 0$ | 350 | 1.5 |
| $R_6$  | $-1.57 \leq \alpha_1 \leq -1.28$ | $-0.38 \leq \alpha_2 \leq 0$ | 350 | 2 |
| $R_7$  | $1.08 \leq \alpha_1 \leq 1.57$ | $-0.46 \leq \alpha_2 \leq 0$ | 350 | 2 |
| $R_8$  | $-1.39 \leq \alpha_1 \leq -1.3$ | $-0.13 \leq \alpha_2 \leq 0$ | 350 | 2.5 |
| $R_9$  | $1.16 \leq \alpha_1 \leq 1.5$ | $-0.43 \leq \alpha_2 \leq -0.1$ | 350 | 2.5 |

$R_{1,9}$ in the $\alpha_1 - \alpha_2$ plane, are defined from experimental bounds in $R_{\gamma\gamma}$ [13].

The radiative process ($B \to X_s\gamma$) strongly restricts the parameter space $M_{H^\pm}$ vs. $\tan \beta$ [14, 15]. The charged Higgs mass is also restricted to be of around 300 GeV [16] for small $\tan \beta$. A global analysis of B meson decays restricts $M_{H^\pm} < 400$ GeV and $\tan \beta < 10$ [17, 18, 19]. Table 1 resumes the $R_i$ regions for the given values of $M_{H^\pm}$ and $\tan \beta$. In each case we set the masses of the neutral Higgses $m_{h_2}$ and $m_{h_3}$ equal to the mass of the charged Higgs $m_{h_2} = m_{h_3} = M_{H^\pm}$.

Once all contributions to CMDM and CEDM are included, we find that for the phenomenologically allowed parameter space the anomalous moments are restricted to be at most of $\Delta \tilde{\kappa} \approx 10^{-2}$ and $\Delta \tilde{d} \approx 10^{-4}$. 

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5. Conclusions
In this work we have studied regions of interest in the $\alpha_1 - \alpha_2$ parameter space, we calculate the contribution to the top anomalous couplings CMDM and CEDM in the context of a general THDM with CP violation. We find that contributions arising from the $Y_t$ Yukawa coupling and from the interference between $M_u$ and $Y_u$ need to be taken into account.

New physics properties of the top quark such as CMDM and CEDM are an excellent probe of different SM extensions. It will be very exciting if any SM deviation is measured. In the future years with more LHC experimental results we will be able to tell more about the top quark structure.

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