Probing Anomalous Top-Gluon Couplings at Colliders

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Anomalous chromomagnetic and chromoelectric dipole moments of the top quark may arise from various high scale theories. We carry out a model independent study of such interactions focusing on the limits that can be obtained from current Tevatron data and the improvements that may be possible at the LHC or at a future Linear Collider.

1 Introduction

The top quark was discovered at the Tevatron proton-antiproton collider at Fermilab in 1995 [1]. The study of its properties continues even today. The top is the heaviest particle in the Standard Model (SM) with a mass \( \sim 175 \text{ GeV} \) which differs widely from those of the other fundamental fermions. This seems to suggest that the top quark may have a role to play in electroweak symmetry breaking and prompts us to question whether the top quark has couplings different from and in addition to those of the other quarks.

Various anomalous couplings of the top have been discussed in Ref. [2]. Of these, the ones that pertain to the QCD-sector form the subject of this study. Large anomalous couplings may arise in a plethora of models [3], contributing to higher order corrections to the \( ttg \) vertex. In a model independent framework, the lowest-dimensional anomalous coupling of the top with the gluon can be parametrized by extra terms in the interaction Lagrangian of the form

\[
L_{\text{int}} \supset \frac{g_s}{\Lambda} F_{\mu\nu}^a i\sigma_{\mu
u}(\rho + i\rho' \gamma_5) T^a t
\]

where \( \Lambda \) denotes the scale of the effective theory. While \( \rho \) represents the anomalous chromomagnetic dipole moment of the top, \( \rho' \) indicates the presence of a (CP-violating) chromoelectric dipole moment. Within the SM, \( \rho' \) is non-zero only at the three-loop level and is, thus, tiny. \( \rho \), on the other hand, receives a contribution at the one-loop level and is \( \mathcal{O}(\alpha_s/\pi) \) for \( \Lambda \sim m_t \). The evidence for a larger \( \rho \) or \( \rho' \) would be a strong indicator of new physics lurking nearby. Whereas both \( \rho \) and \( \rho' \) can, in general, be complex, note that any imaginary part thereof denotes absorptive contributions and would render the Lagrangian non-Hermitian. We desist from considering such a possibility.

The phenomenological consequences of such anomalous couplings have been considered earlier in Ref. [4]. We reopen the issue in light of the improved measurements of top quark mass and \( t\bar{t} \) cross-section and the first reported measurement of \( t\bar{t} \) invariant mass.

2 Hadron Collider Prospects

The inclusion of a chromomagnetic moment term leads to a modification of the vertex factor for the usual \( ttg \) interaction to

\[
ig_s[\gamma^\alpha + (2i\rho/\Lambda) \sigma^{\alpha\beta} k_\mu] T^a t
\]

where \( k \) is the momentum of the gluon coming into the vertex. An additional quartic interaction involving two top quarks and two gluons is also generated with the corresponding vertex factor being

\[
(2i g_s^2 \rho/\Lambda) f_{abc} \sigma^{\alpha\beta} T^c.
\]

The changes in the presence of the chromoelectric dipole moment term are analogous, with \( \rho \) above being replaced by \( (i\rho' \gamma_5) \).
At a hadron collider, the leading order contributions to $t\bar{t}$ production come from the $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$ sub-processes. Detailed expressions for the differential cross-sections can be found in Ref. [5] as well as Ref. [4]. Using these results, we compute the expected $t\bar{t}$ cross-section at the Tevatron and the LHC. We use the CTEQ6L1 parton distribution sets [6] with $m_t$ as the scale for both factorization as well as renormalization. For a consistent comparison with the cross-section measurement reported by the CDF collaboration [7], we use $m_t = 172.5$ GeV for the Tevatron analysis. For the LHC analysis, though, we use the updated value of $m_t = 173.1$ GeV, obtained from combined CDF+DØ analysis [8]. To incorporate the higher order corrections absent in our leading order results, we use the $K$-factors at the NLO+NLL level calculated by Cacciari et. al. [9]. Once this is done, the theoretical errors in the calculation owing to the choice of PDFs and scale are approximately 7-8% for the Tevatron and 9-10% for the LHC [9]. However, the estimates reported for the LHC operating at 7 TeV, are only leading order ones since NLO calculations for these energies are, so far, unavailable.

2.1 Tevatron Results

At the Tevatron, the dominant contribution accrues from the $q\bar{q}$ initial states, even on the inclusion of the dipole moments. Fig.1(a) displays the parameter space that is still allowed by the Tevatron data, namely [7]

$$\sigma_{t\bar{t}}(m_t = 172.5 \text{ GeV}) = (7.50 \pm 0.48) \text{ pb}. \quad (2)$$

The central region of the plot shows that the data allows for large values of dipole moments. This is essentially due to cancellations between various terms contributing to the cross-section.

Figure 1: (a) The region in $(\rho/\Lambda)-(\rho'/\Lambda)$ plane allowed by the Tevatron data [7] at the 1-σ, 3-σ and 5-σ level. (b) $t\bar{t}$ production rates for the Tevatron ($\sqrt{s} = 1.96$ TeV). The horizontal lines denote the CDF central value and the 3-σ interval [7].

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*In the absence of a similar calculation incorporating anomalous dipole moments, we use the same $K$-factor as obtained for the SM case. While this is not entirely accurate, given the fact that the color structure is similar the error associated with this approximation is not expected to be large.

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Having seen the extent to which cancellations may, in principle, be responsible for hiding the presence of substantial dipole moments, we now restrict ourselves to the case where only one of $\rho$ and $\rho'$ may be non-zero. If only one of the two couplings is to be non-zero, we may rescale $\rho, \rho' = 0, \pm 1$ and, thus, reduce the parameter space to one dimension ($\Lambda$). $\rho' = \pm 1$ are equivalent as the the cross-section only depends on even powers of $\rho'$.

Fig. 1(b) exhibits the corresponding dependence of the total cross-section at the Tevatron on $\Lambda$ for various combinations of ($\rho, \rho'$). It can be seen that $\Lambda \lesssim 7400$ GeV can be ruled out at 99% confidence level for the $\rho = +1$ case. For $\rho = -1$ on the other hand, $\Lambda \lesssim 9000$ GeV can be ruled out at the same confidence level. One expects similar sensitivity for $\rho = +1$ and $\rho = -1$. The difference essentially owes its origin to the slight discrepancy between the SM expectations (as computed with our choices) and the experimental central value. The sensitivity to chromoelectric moment is low. This is understandable as the corresponding contribution is suppressed by at least $\Lambda^2$.

The cross-sections considered above depend on powers of $\Lambda$ up to $\Lambda^4$. However, the Lagrangian considered in Eqn. 4 contains only the lowest dimensional anomalous operators of an effective theory. Higher dimensional operators [10], if included in the Lagrangian, could change the behaviour of the cross-sections and hence the conclusions drawn from Fig. 1(b). A closer examination of this issue (see Fig. 2(a)) reveals that that were we to neglect $O(\Lambda^{-2})$ terms, the shape of the curves would indeed change but the limits on $\Lambda$ for either of $\rho = \pm 1$ would hardly alter.

Yet another measurement reported by the Tevatron is the invariant mass distribution [11]. This data can be used to put further constraints on values of $\rho$ and $\rho'$. In the reported measurement, the first bin which extends in the range 0-350 GeV also has a non-zero number of events, an artefact of experimental errors associated with the reconstruction of the $t\bar{t}$ events. For our analysis, we exclude this bin. Further, we normalize the our calculated $m_{t\bar{t}}$ distribution so that for the SM case it matches the CDF simulation. As a statistic, we

Figure 2: (a) Comparison of production rates obtained at the Tevatron with truncated cross-sections (up to $O(\Lambda^{-1})$; denoted by subscript $\Lambda$ in the key) and full cross-sections (all orders in $\Lambda$). (b) $\chi^2$ per degree of freedom obtained by fitting the $m_{t\bar{t}}$ spectrum.
consider a $\chi^2$ defined through

$$\chi^2 = \sum_{i=2}^{9} \left( \frac{\sigma_{th}^i - \sigma_{obs}^i}{\delta \sigma_i} \right)^2$$

where the sum runs over the bins and $\sigma_{th}^i$ is the number of events expected in a given theory (defined by the values of $\rho$, $\rho'$, $\Lambda$) in a particular bin. $\sigma_{obs}^i$ and $\delta \sigma_i$ are the observed event numbers and the errors therein. The $\chi^2$ values thus obtained are plotted as function of $\Lambda$ in Fig.2(b).

It is interesting to note that the $\rho = -1$ case gives a better fit than the SM, over a large range of $\Lambda$ values while $\rho = +1$ is now strongly disfavoured for much higher values of $\Lambda$. Even for the chromoelectric moment case ($\rho' \neq 0$), the increase in sensitivity is evident. However, in all of this, we wish to tread with caution. This distribution has been constructed on the basis of only 2.7 $fb^{-1}$ of data. Robust limits may be obtained once more statistics has been accumulated and a more realistic simulation, with the inclusion of the effects of dipole moment terms, has been carried out.

### 2.2 LHC Sensitivity

At the LHC, the $gg$ flux dominates, especially at smaller $\hat{s}$ values. In Fig.3 we present the cross-sections at the LHC for various values of the proton-proton center-of-mass energy $\sqrt{s}$. In the absence of any data, we can only compare these with the SM expectations and the estimated errors [12].

![Figure 3: $t\bar{t}$ production rates for the LHC as a function of the new physics scale $\Lambda$. Panels from left to right correspond to $\sqrt{s} = 7, 10, 14$ TeV. The horizontal lines show the SM expectation and the 10% and 20% intervals as estimates of errors in the measurement [12].](image)

For non-zero $\rho'$, an early run of the LHC with $\sqrt{s} = 7$ TeV (Fig.3a) would be sensitive to $\Lambda \lesssim 2700$ GeV. The improvement of the sensitivity with the machine energy is marginal at best. For $\rho = +1$, naively a sensitivity up to about $\Lambda \sim 10$ TeV could be expected. For $\rho = -1$, on the other hand, it appears that the best that the LHC can do is to rule out (for $\rho = -1$) $\Lambda \lesssim 8$ TeV. This, however, should be compared with the Tevatron results which have already ruled out $\Lambda \lesssim 9$ TeV.

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2.3 Summary of Limits from Hadron Colliders

Rephrasing the above results in terms of notation commonly used in literature:

\[
\frac{1}{\Lambda} (\rho + i \rho') \leftrightarrow \frac{1}{2m_t} (\kappa + i \tilde{\kappa}) : \quad -0.038 \leq \kappa \leq 0.034 \quad \text{and} \quad |\tilde{\kappa}| \leq 0.12
\]

3 Linear Collider Prospects

An electron-positron collider would be the ideal ground for probing anomalous electroweak couplings of the top quark. However, anomalous top-gluon couplings would play a role in the process \(e^+e^- \rightarrow ttg\). This has been studied in Refs. [13] and [14], where it was shown that the energy distribution of the gluon is sensitive to such anomalous couplings. Limits on couplings were obtained by fitting the energy spectrum of the gluon assuming that there is no excess in the total production cross-section. Some of the results from Ref. [14] are shown in Fig. 4.

![Figure 4](image)

(a) (b)

Figure 4: Reproduced from Ref. [14]. Shows the 95% CL allowed region for (a) \(\sqrt{s} = 500\) GeV ; \(L = 50 \, fb^{-1}\) (solid), 100 \(fb^{-1}\) (dotted) ; \(E_g^{min} = 25\) GeV. (b) \(\sqrt{s} = 1\) TeV ; \(L = 100 \, fb^{-1}\) (solid), 200 \(fb^{-1}\) (dotted) ; \(E_g^{min} = 25\) GeV.

Considering only one of \(\kappa\) and \(\tilde{\kappa}\) to be non-zero at a time, the dotted curve in Fig.4(a) implies \(-0.015 \leq \kappa \leq 0.033\) and \(|\tilde{\kappa}| \leq 0.47\). With an increase in center-of-mass energy and luminosity, this limit may be improved as indicated by Fig.4(b). Here, the dotted curve leads to \(-0.024 \leq \kappa \leq 0.026\) and \(|\tilde{\kappa}| \leq 0.14\). Comparing this to the limits expected from hadron colliders listed in the previous section, it can be seen that, at a linear collider, better sensitivity may be expected for \(\kappa\) but not for \(\tilde{\kappa}\).

At a linear collider, there also exists the possibility of collisions using a polarized beam. This too was studied in Ref. [14]. However it was found that, using a polarized beam does not yield better limits on either chromomagnetic or chromoelectric dipole moments as compared to what can be obtained with unpolarized beams.

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