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Probing top anomalous couplings at the Tevatron and the Large Hadron Collider

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Abstract. Chromomagnetic and chromoelectric dipole interactions of the top quark are studied in a model-independent framework. Limits are set on the scale of new physics that might lead to such contributions using latest Tevatron measurements of the $t\bar{t}$ cross-section. It is demonstrated that the invariant mass distribution is a sensitive probe. Prospects at the LHC are examined. It is shown that, for unitarized amplitudes, an increase in the LHC energy is of little importance, while the accumulation of luminosity plays a crucial role.

Keywords. Top; anomalous; Tevatron; Linear Hadron Collider.

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1. Introduction

The Standard Model (SM) embodies our current understanding of the fundamental constituents of the Universe and their interactions. This model is well tested up to the energy scale of a few hundred GeVs and experiments have shown many of its predictions to be astoundingly accurate. However, in spite of this stupendous success, certain questions remain unanswered. Among them are questions regarding the mechanism responsible for giving masses to fundamental particles.

Within the SM, the generation of masses is explained by the spontaneous breaking of the electroweak symmetry and the Higgs mechanism. However, no such Higgs scalar has been found yet. Furthermore, the SM fails to explain why, even though the underlying mechanism is the same, there is a difference of six orders of magnitude between the masses of the lightest fermion (electron) [1] and the heaviest one (top quark). The Yukawa couplings of the fermions with the Higgs are parameters in the SM and cannot be explained or predicted by the theory.

It is possible to bring about electroweak symmetry breaking (EWSB) without introducing a new fundamental field such as the Higgs [2]. What is important to note is that, any theory that provides a mechanism for generation of masses must have a large coupling to

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the top quark. Consequently, even in the absence of an actual observation of the Higgs boson, experiments with the top may be used to probe the EWSB mechanism. Not only is the top quark the heaviest particle in the SM with a mass ~175 GeV, its mass differs widely from those of the other fermions (the next heaviest is the b-quark with a mass of 4.2 GeV [3]). This prompts us to examine whether the top quark has couplings different from and in addition to those of the other quarks.

At the Tevatron proton–antiproton collider at Fermilab, the mass and charge of the top quark have been measured reasonably well [4,5]. But, the high threshold for top production has meant that its couplings are still not well measured. The possibility that the top quark has anomalous couplings is still open. Once the Large Hadron Collider at CERN comes into operation, precise measurements of top couplings and detection of anomalous couplings will be possible.

Various anomalous couplings of the top have been discussed in ref. [6]. Of these, the ones that pertain to the QCD-sector would be expected to modify the production rates significantly and, thus, to be probed during the early phase of the LHC. On the other hand, modifications of the electroweak couplings would play only a sub-dominant role in $t\bar{t}$ production and it is the decay patterns that would be affected more by them. Consequently, a search for the latter type would require both a thorough understanding of the detector as well as the accumulation of large statistics. Given this, we concentrate here on the former set.

Large anomalous couplings may arise in a plethora of models. Prominent among these are scenarios of dynamical EWSB. Mechanisms for dynamic breaking of electroweak symmetry through the formation of $t\bar{t}$ condensates are discussed in ref. [7]. Such scenarios require the top quark to have non-QCD 'strong' interactions and give rise to interaction terms such as $\bar{t}t\bar{t}t$ and $\bar{t}t\bar{b}b$ which then contribute to the higher-order corrections to the ttg vertex. Contributions may also arise from theories with additional heavy fermions that couple to the top. Examples include, but are not limited to, little Higgs models [8,9] or models with extra space-time dimensions [10–12]. Another possibility is the SM augmented by colour-triplet or colour-sextet scalars that have Yukawa couplings with the top quark [13].

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

$$\mathcal{L}_{\rm int} \ni \frac{g_s}{\Lambda}\, F_a^{\mu\nu}\, \bar{t}\sigma_{\mu\nu}(\rho + i\rho'\gamma_5)\, T_a\, t, \tag{1}$$

where Λ denotes the scale of the effective theory. While ρ represents the anomalous chromomagnetic dipole moment of the top, ρ' indicates the presence of a (CP-violating) chromoelectric dipole moment. Within the SM, ρ' is non-zero only at the three-loop level and is, thus, tiny. ρ, 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 ρ or ρ' would thus be a strong indicator of new physics lurking nearby. Whereas both ρ and ρ' 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. [14]. However, 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. Analytic calculation

The inclusion of a chromomagnetic moment term leads to a modification of the vertex factor for the usual ttg interaction to $ig_s[\gamma^\alpha + (2i\rho/\Lambda)\,\sigma^{\alpha\mu}k_\mu]T^a$ 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 [15] with the corresponding vertex factor being $(2ig_s^2\rho/\Lambda)f_{abc}\sigma^{\alpha\beta}T^c$. The changes in the presence of the chromoelectric dipole moment term are analogous, with ρ being replaced by $(i\rho'\gamma_5)$.

At a hadron collider, the leading order contributions to $t\bar{t}$ production come from the $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ subprocesses. Summing (averaging) over spin and colour degrees of freedom and defining $\Theta_\pm = 1 \pm \beta^2\cos^2\theta$ where $\beta = \sqrt{1 - 4m_t^2/\hat{s}}$ and θ are, respectively, the velocity and scattering angle of the top in the parton centre-of-mass frame, the differential cross-sections can be expressed as

$$\begin{aligned}
\left(\frac{2\hat{s}}{\pi\alpha_s^2\beta}\right)\frac{\mathrm{d}\hat{\sigma}_{q\bar{q}}}{\mathrm{d}\cos\theta} &= \frac{2}{9}\Theta_+ + \frac{8}{9}\frac{m_t^2}{\hat{s}} \\
&\quad + \frac{32\rho m_t}{9\Lambda} + \frac{8\rho^2}{9\Lambda^2}\left(\hat{s}\Theta_- + 4m_t^2\right) + \frac{8\rho'^2}{9\Lambda^2}\left(\hat{s}\Theta_- - 4m_t^2\right), \\
\left(\frac{2\hat{s}}{\pi\alpha_s^2\beta}\right)\frac{\mathrm{d}\hat{\sigma}_{gg}}{\mathrm{d}\cos\theta} &= \frac{2}{3\Theta_-}\left(1+\frac{4m_t^2}{\hat{s}}+\frac{m_t^4}{\hat{s}^2}\right) - \left(\frac{1}{3}+\frac{3}{16}\Theta_+ + \frac{3m_t^2}{2\hat{s}} + \frac{16m_t^4}{3\hat{s}^2}\frac{\Theta_+}{\Theta_-^2}\right) \\
&\quad + \frac{\rho\, m_t}{\Lambda}\left(-3 + \frac{16}{3\Theta_-}\right) + \frac{\rho^2}{\Lambda^2}\left[\frac{7}{3}\hat{s} + m_t^2\left\{-6 + \frac{34}{3\Theta_-}\right\}\right] \\
&\quad + \frac{\rho'^2}{\Lambda^2}\left[\frac{7}{3}\hat{s} + \frac{2m_t^2}{3\Theta_-}\right] \\
&\quad + \frac{\rho}{\Lambda}\left(\frac{\rho^2}{\Lambda^2} + \frac{\rho'^2}{\Lambda^2}\right)m_t\left(\frac{28}{3}\hat{s} - \frac{20}{3\Theta_-}m_t^2\right) \\
&\quad + \frac{4}{3}\left(\frac{\rho^2}{\Lambda^2} + \frac{\rho'^2}{\Lambda^2}\right)^2\left(\hat{s}^2\Theta_- - m_t^2\hat{s} + \frac{4}{\Theta_-}m_t^4\right).
\end{aligned} \tag{2}$$

In each case, the first line refers to the SM result (we do not exhibit the electroweak contribution for the $q\bar{q}$-initiated process as it remains unaltered) and the rest encapsulate the consequences of the anomalous dipole moments.

It should be noted that there are neither terms with an odd power of ρ' nor do the expressions show any possibility of a forward–backward asymmetry, even in the presence of a non-zero ρ'. The two facts are inter-related. With ρ (ρ') representing a parity-even (odd) operator, clearly, terms odd in $\cos\theta$ have to be proportional to odd powers of ρ'. On the other hand, with the chromoelectric dipole moment being a CP-violating one, an odd power of ρ' would denote a CP-odd (and T-odd) observable. It is easy to see that no such observable can be constructed out of the four momenta (the two initial state hadrons and the tops) alone. If we had the ability to measure the polarizations, that possibility would open up too [16]. Although preliminary efforts in this direction are underway [17], the accumulated statistics is unlikely to be enough to look for this subtle effect. Similarly, the presence of absorptive parts of ρ (or ρ') would have allowed for the existence of such terms (essentially by changing the properties of the operator under time reversal).

A further feature is the growth of the cross-sections with energy as is expected in a theory with dimension-five (or higher) operators. While this may seem unacceptable on account of a potential loss of unitarity [18], one should realize that the theory of eq. (1) is only an effective one and is expected to be superseded beyond the scale Λ. While unitarity may be restored by promoting ρ (ρ') from constants to form-factors with appropriate powers of $(1+\hat{s}/\Lambda^2)$, this is an ad-hoc measure as the mechanism of unitarity restoration is intricately related to the precise nature of the ultraviolet completion. We desist from doing this with the *a posteriori* justification that the limits of sensitivity for ρ (as described in the next section) are far beyond the typical subprocess energies ($\hat{s}/\Lambda \ll 1$). Furthermore, note that the terms of $\mathcal{O}(\rho)$ do respect partial wave unitarity. These terms [19] appear only as a result of interference between pure QCD and the dipole contributions, and owing to the different chirality structures of the operators, have to be proportional to m_t (thereby suppressing the growth with energy).

3. Numerical analysis

Armed with the results of the previous section, we compute the expected $t\bar{t}$ cross-section at the Tevatron as well as the LHC. To this end, we use the CTEQ6L1 parton distribution sets [20] 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 [21], 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 the combined CDF+DØ analysis [4]. To incorporate the higher order corrections absent in our leading order results, we use the K-factors at the NLO+NLL level [22] calculated by Cacciari *et al* [23]. Once this is done, the theoretical errors in the calculation owing to the choice of PDFs and scale are $\sim$ 7–8% for the Tevatron and 9–10% for the LHC [23]. For the LHC operating at 7 TeV, though, we use the approximate NNLO cross-section as reported in ref. [24].

3.1 *Tevatron results*

At the Tevatron, the dominant contribution accrues from the $q\bar{q}$ initial states, even on the inclusion of the dipole moments. While the $\mathcal{O}(\rho^2, \rho'^2)$ terms in $\mathrm{d}\sigma/\mathrm{d}\cos\theta$ are always positive (see eq. (2)), the flat $\mathcal{O}(\rho)$ term can flip sign with ρ. This implies that for $\rho > 0$, the change in the cross-section, $\delta\sigma$, is positive. This severely constrains any deviation of the anomalous couplings in that direction. On the other hand, for $\rho < 0$, large cancellations may occur between various pieces of the cross-section. Consequently, substantial negative ρ could be admitted, albeit correlated with a substantial ρ'. This is exhibited by figure 1a which displays the parameter space that is still allowed by the Tevatron data, namely [21]

$$\sigma_{t\bar{t}}(m_t = 172.5\,\mathrm{GeV}) = (7.50 \pm 0.48)\,\mathrm{pb}. \tag{3}$$

The near elliptical shape of the contours is but a reflection of the fact that, at the Tevatron, the $q\bar{q}$ contribution far supersedes the gg one.

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

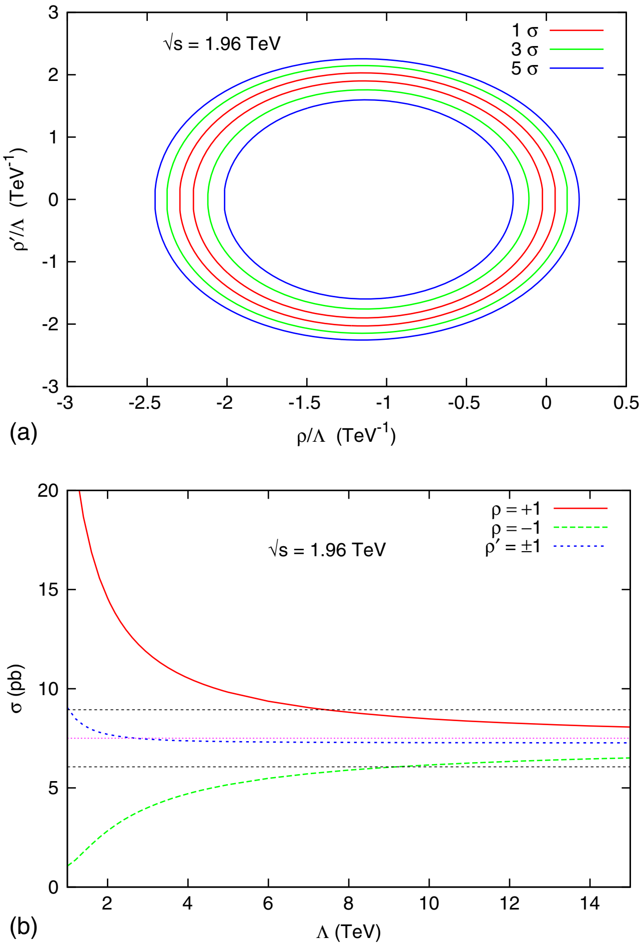

Figure 1. (**a**) The region in (ρ/Λ)–(ρ'/Λ) plane allowed by the Tevatron data [21] at the 1-σ, 3-σ and 5-σ levels. (**b**) $t\bar{t}$ production rates for the Tevatron ($\sqrt{s} = 1.96$ TeV). The horizontal lines denote the CDF central value and the 3-σ interval [21].

only one of ρ and ρ' may be non-zero. While this might seem a gross simplification, it is not really so. For one, with the chromomagnetic moment manifesting itself at $\mathcal{O}(\Lambda^{-1})$ and the chromoelectric moment appearing in the cross-sections only at $\mathcal{O}(\Lambda^{-2})$, it is obvious that, for large Λ, the former would, typically, leave a larger imprint. Secondly, it is extremely unlikely that the couplings conspire to be just so that large cancellations take place. This is particularly true because, for a generic underlying ultraviolet completion, one would expect the chromoelectric moment operator to appear at a higher order of perturbation than the chromomagnetic one. On the other hand, the situation could be reversed if there is an underlying symmetry (*à la* the symmetry proposed in ref. [26] to account for neutrino magnetic moments) that prevents ρ from appearing while allowing a non-zero ρ'.

If only one of the two couplings are to be non-zero, we may rescale $\rho, \rho' = 0, \pm 1$ and, thus, reduce the parameter space to one dimension (Λ). Of course, $\rho' = \pm 1$ are equivalent. Figure 1b exhibits the corresponding dependence of the total cross-section at the Tevatron on Λ for various combinations of (ρ, ρ'). For $\rho = +1, -1$, the near-monotonic dependence on Λ is reflective of the dominance of the $\mathcal{O}(\rho/\Lambda)$ term. This is particularly true for $\Lambda/\rho \gtrsim 3$ TeV.

The low sensitivity to the chromoelectric moment is understandable in view of the fact that the corresponding contribution is suppressed by at least Λ^2. Furthermore, unlike in the case of the chromomagnetic moment, the $q\bar{q} \to t\bar{t}$ cross-section in this case suffers an additional cancellation owing to the chirality structure (see eq. (2)). With $\hat{s}$ at the Tevatron being only slightly greater than $4m_t^2$, this cancellation is quite significant.

Note that, for $\rho \neq 0$, while figure 1a shows a second range (close to $\rho/\Lambda \sim -2.2\,\text{TeV}^{-1}$) consistent with experimental observation, the existence of the same is not apparent in figure 1b. As can be easily appreciated, for smaller Λ, the $\mathcal{O}(\rho^2/\Lambda^2)$ term gets progressively more important, leading to a rapid growth in the total cross-section for $\rho > 0$ and a cancellation between the two leading Λ-dependent terms for $\rho < 0$. Consequently, for smaller values of Λ (not shown in the plot), the lowest curve in figure 1b would actually suffer a turnaround, rendering it consistent with the measurements for a certain range of Λ. However, one should not be lead on too far by this. It is the $\mathcal{O}(\Lambda^{-2})$ contributions that are largely responsible for this second region of consistency. On the other hand, the Lagrangian considered in eq. (1) contains only the lowest-dimensional anomalous operators of an effective theory. Higher-dimensional operators [27], if included in the Lagrangian, could change the behaviour of the cross-sections and hence the conclusions drawn from figure 1b. A closer examination of this issue (see figure 2) reveals that were we to neglect $\mathcal{O}(\Lambda^{-2})$ terms in eq. (2), the shape of the curves would indeed change considerably [28], but the limits on Λ for either of $\rho = \pm 1$ would hardly alter. In other

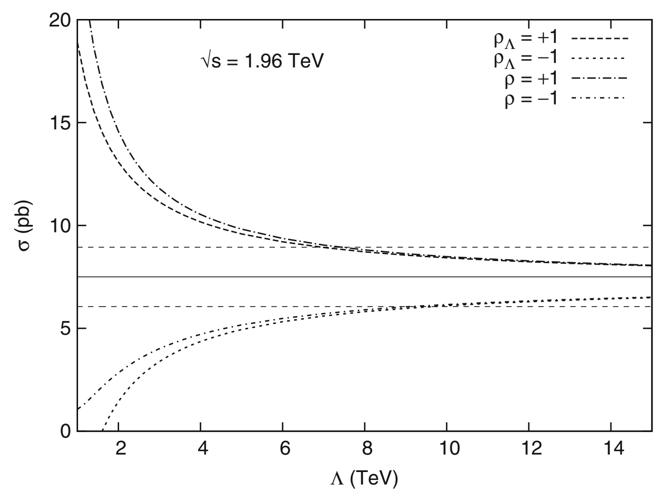

Figure 2. Comparison of production rates obtained at the Tevatron with truncated cross-sections (up to $\mathcal{O}(\Lambda^{-1})$; denoted by subscript Λ in the key) and full cross-sections (all orders in Λ).

words, the sensitivity limits are overwhelmingly dominated by the $\mathcal{O}(\rho/\Lambda)$ terms, thus making them quite robust. In fact, the change in the limits from inclusion of higher-order terms are well below the theoretical errors from sources such as the dependence on the factorization/renormalization scales, choice of PDF etc. To be quantitative, $\Lambda \lesssim 7400$ 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. Of course, restricting to $\mathcal{O}(\Lambda^{-1})$ eliminates ρ' altogether. However, sensitivity to ρ' may still be obtained by including absorptive pieces and/or by considering polarized scattering.

3.2 *LHC sensitivity*

At the LHC, it is the gg flux that rules the roost, especially at smaller $\hat{s}$ values. Moreover, at high centre-of-mass energies, the gluon-initiated cross-sections grow as $\hat{s}/\Lambda^4$, whereas the $q\bar{q}$-initiated cross-sections remain, at best, constant with $\hat{s}$. Consequently, it is fair to say that the $gg \to t\bar{t}$ subprocess dominates throughout. In figure 3, we present the corresponding cross-sections at the LHC as a function of Λ for various values of the proton–proton

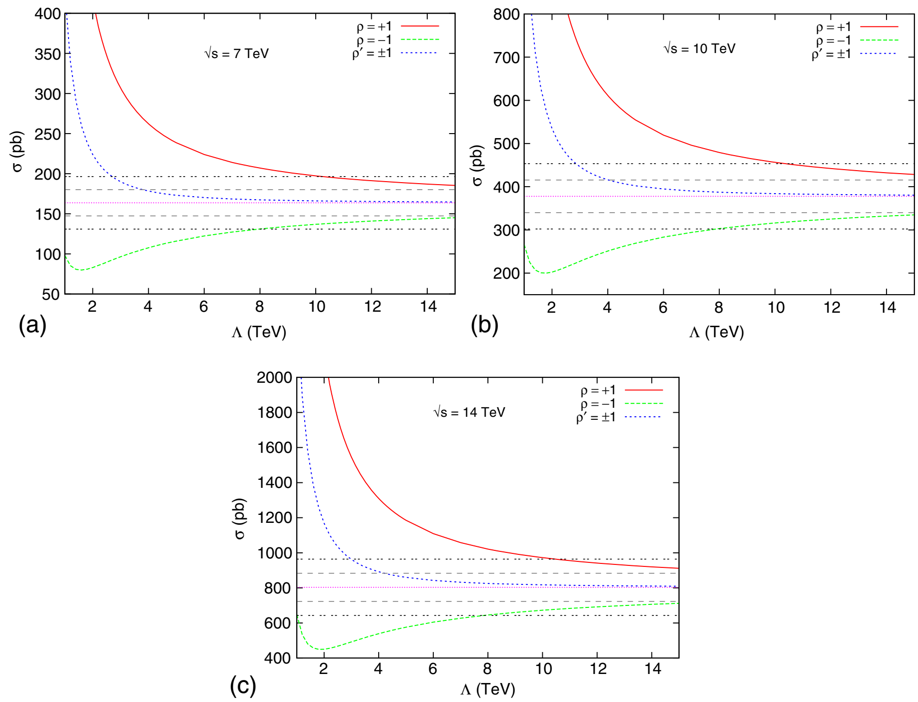

Figure 3. $t\bar{t}$ production rates for the LHC as a function of the new physics scale Λ. (**a**) corresponds to $\sqrt{s} = 7$, (**b**) $\sqrt{s} = 10$ and (**c**) $\sqrt{s} = 14$ TeV. The horizontal lines show the SM expectation and the 10% and 20% intervals as estimates of errors in the measurement [29].

centre-of-mass energy $\sqrt{s}$. In the absence of any data, we can only compare these with the SM expectations and the estimated errors. Experimental errors due to systematic and statistical uncertainties are expected to be between 20 and 30% for an integrated luminosity of 20 pb^{-1} at $\sqrt{s}$ = 10 TeV [29] (the errors for other values of $\sqrt{s}$ are similar) and dominate the theoretical errors quoted earlier. Since experimental errors are expected to decrease with better calibration of the detectors and increase in statistics, we choose to display 10% (optimistic) and 20% error bars for comparison.

Setting bounds on the chromoelectric dipole moment now becomes possible. Much of this is due to the fact that the $gg \to t\bar{t}$ amplitude is not as chirally suppressed as the $q\bar{q} \to t\bar{t}$ one (see eq. (2)). For non-zero ρ', even an early run of the LHC with $\sqrt{s}$ = 7 TeV (figure 3a) would be sensitive to $\Lambda \lesssim 2700\,\text{GeV}$. Unfortunately, the improvement of the sensitivity with the machine energy is marginal at best.

As for the chromomagnetic moment, the story is more complicated. For $\rho = +1$, naively a sensitivity up to about $\Lambda \sim 10\,\text{TeV}$ could be expected. A higher operative energy for the LHC renders it more suitable to the chromomagnetic moment as long as $\rho = +1$. This growth in sensitivity is a reflection of the growing importance of the higher-order (in ρ/Λ) terms as the energy is increased [30]. However, the magnitude of the increase in sensitivity with the pp centre-of-mass energy is small. This can be understood by looking at eq. (2). The SM as well as the $\mathcal{O}(\rho/\Lambda)$ terms in the cross-section fall with $\hat{s}$. At lower values of $\hat{s}$, the SM piece falls faster. However, in the higher $\hat{s}$ regime, both have similar behaviour and thus the increase in sensitivity that can be obtained by increasing the centre-of-mass energy is only marginal.

For $\rho = -1$, on the other hand, the situation is reversed. The contrasting behaviour is easy to understand in terms of the constructive (destructive) interferences with the SM amplitude in the two cases. The aforementioned cancellation between various orders reappears in a more complicated guise even for the $gg \to t\bar{t}$ case. On account of this, it appears that the best that the LHC can do is to rule out (for $\rho = -1$) $\Lambda \lesssim 8\,\text{TeV}$. This, however, should be compared with the Tevatron results which have already ruled out $\Lambda \lesssim 9\,\text{TeV}$.

While the discussion above was based on the full cross-sections as listed in eq. (2), the situation changes somewhat if one were to truncate contributions beyond $\mathcal{O}(\Lambda^{-1})$. In table 1, we display the bounds on Λ that may be reached, with and without such a truncation, for the three different stages of LHC operation. In reaching these bounds, we

Table 1. The values of Λ (in TeVs) that would lead to a 20% deviation in the cross-section from the SM expectations, for $\rho = \pm 1$ and $\rho' = 0$. In each case, the limits are shown as calculated with the full cross-sections of eq. (2) as well as those obtained from the expressions truncated at the $\mathcal{O}(\Lambda^{-1})$ level.

	$\sqrt{s} = 7\,\text{TeV}$		$\sqrt{s} = 10\,\text{TeV}$		$\sqrt{s} = 14\,\text{TeV}$	
	Full	Trunc.	Full	Trunc.	Full	Trunc.
$\rho = +1$	10.20	9.20	10.45	9.25	10.50	9.30
$\rho = -1$	8.00	9.20	7.95	9.25	7.85	9.30

have assumed that a 20% deviation constitutes a discernible shift. For $\rho = +1$, a small increase in sensitivity is obtained by increasing the machine energy, as with the untruncated cross-sections. The most interesting feature, however, is that for $\rho = -1$, with truncated cross-sections, one gets an improvement in the sensitivity on increasing the machine energy. This is contrary to the trend observed when the full cross-sections are considered. This is but yet another indication of the importance of the terms of order $1/\Lambda^2$ and greater and their role in cancellations between various pieces in the cross-section at higher values of $\hat{s}$. However, owing to the nature of the gg and $q\bar{q}$-fluxes, most of the cross-section accrues from relatively smaller values of $\hat{s}$. Hence the magnitude of the change is tiny.

In fact, even with a several fold increase in the LHC energy, the sensitivity would not increase much. It is amusing to note that, if LHC were a $p\bar{p}$ collider instead, the use of the full matrix-element-squared would have entailed a substantial increase in the sensitivity with energy, although the situation for the truncated case would have remained quite similar. The use of the full matrix elements would have entailed using subprocess cross-sections that grow with $\hat{s}$. In the present situation, this has been offset by the rapidly falling antiquark and gluon densities at large x-values. For a $p\bar{p}$ collider, the $\bar{q}$ densities would not fall off so fast, resulting in a growth of the cross-section. On the other hand, by truncating the cross-section to $\mathcal{O}(\rho)$, we essentially ensure that the subprocess cross-sections do not violate unitarity. The truncated subprocess cross-sections actually fall with $\hat{s}$ at approximately the same rate as the SM ones. This ensures that the relative deviation does not grow even with an increase in the $p\bar{p}$ centre-of-mass energy.

3.3 *Use of differential distributions*

So far, we have only considered the total $t\bar{t}$ cross-section and the deviations therein as a possible signal for the existence of anomalous dipole moments. There exist other observables that can be constructed and studied even in the complex detector environment of a hadron collider. The invariant mass distribution of the final-state particles is one such. In 2009, the CDF Collaboration reported the first measurement of the $t\bar{t}$ invariant mass ($m_{t\bar{t}}$) distribution [31]. These data can be used to put further constraints on ρ and ρ' values.

The CDF Collaboration reports the measurement in 9 bins between 0 and 1400 GeV (figure 1 and table III in ref. [31]) assumimg $m_t = 175$ GeV with 2.7 fb^{-1} worth data. Note that 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 as well as of effects due to final-state radiation. For our analysis, we exclude this bin. The experimental effects are simulated so that the $m_{t\bar{t}}$ distribution for the SM matches with the CDF expectations. As a statistic, we consider a χ^2 defined through

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

where the sum runs over the bins and $\sigma_i^{\rm th}$ is the number of events expected in a given theory (defined by the values of ρ, ρ', Λ) in a particular bin. $\sigma_i^{\rm obs}$ and $\delta\sigma_i$, on the other hand, are the observed event numbers and the errors therein. The χ^2 values thus obtained are plotted in figure 4 as a function of Λ.

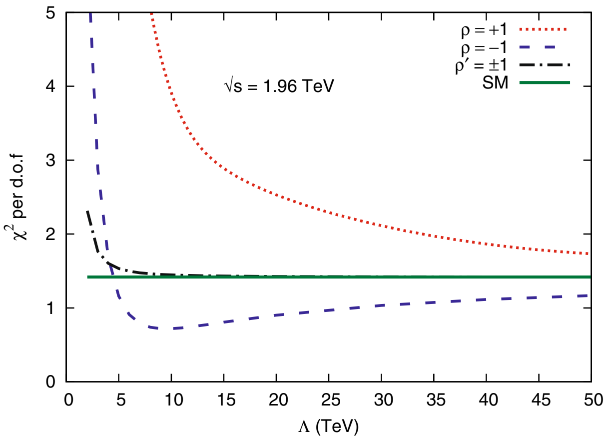

Figure 4. χ^2 per degree of freedom.

It is interesting to note that the $\rho = -1$ case gives a better fit than the SM, over a large range of Λ values. Thus the data could be claimed to favour such a scenario! On the other hand, $\rho = +1$ is now strongly disfavoured for much higher values of Λ, thereby exhibiting the aforeclaimed enhanced sensitivity of the $m_{t\bar{t}}$ distribution. 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.

At the LHC too, differential distributions will have a role to play in enhancing the sensitivity to different kinds of new physics scenarios and discriminating between them. From figure 3b one can see that in pp collisions at $\sqrt{s} = 10$ TeV, various combinations $(\rho, \rho') = (1, 0), (0, \pm 1)$ may give rise to positive deviations of the order of, say 15–20% in the total cross-section, albeit for wildly different values of Λ. How can one distinguish between them? To answer this question, we once again turn to the invariant mass distribution and consider the full set of expressions of eq. (2), rather than the truncated ones. As figure 5a shows, the distributions do indeed diverge significantly for large $m_{t\bar{t}}$. The two anomalous cross-sections depicted are roughly equal and deviate by approximately 20% from the SM one. One might argue though that small differences in the spectrum could (a) rise from various effects within the SM and/or experimental resolutions and (b) get washed away as a result of poor statistics. The second objection is countered by the observation that significant deviations are associated with a sizable event rate, even for a moderate value of the integrated luminosity. This deviation is emphasized further if one considers the ratio

$$\left(\frac{1}{\sigma}\,\frac{\mathrm{d}\sigma}{\mathrm{d}m_{t\bar{t}}}\right) \Big/ \left(\frac{1}{\sigma_{\mathrm{SM}}}\,\frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}m_{t\bar{t}}}\right). \tag{4}$$

This observable has the benefit of using normalized quantities so that some of the systematic errors such as those due to luminosity measurements or lack of precise knowledge of

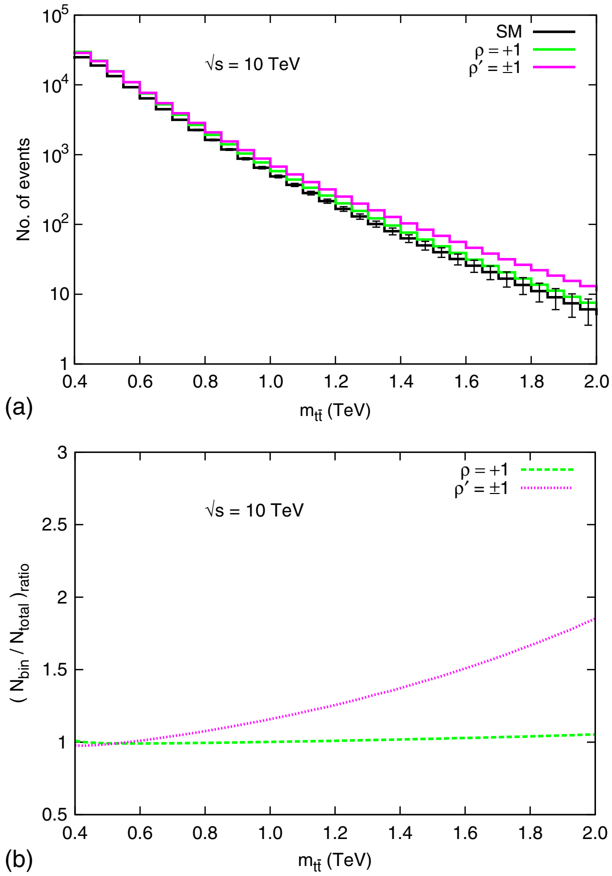

Figure 5. (**a**) The $m_{t\bar{t}}$ spectrum for the LHC at $\sqrt{s} = 10$ TeV along with the 1-σ Gaussian error bar for the SM. (**b**) The ratio of the normalized $m_{t\bar{t}}$ spectra (see eq. (4)). In each case, the two anomalous sets refer to $(\rho, \rho', \Lambda) = (+1, 0, 11\,\text{TeV})$ and $(0, \pm 1, 3\,\text{TeV})$ respectively. An integrated luminosity of 300 pb^{-1} has been assumed.

the parton densities are largely removed. As a perusal of figure 5b shows, the qualitative differences between the cases stand out starkly. It should be noted that the fact of the normalized distribution for the $\rho = +1$ case being very closely aligned with the SM one is not accidental, but just a consequence of the fact that it corresponds to a larger value of Λ compared to the other case. Consequently, the new physics contribution is dominated by the $\mathcal{O}(\rho/\Lambda)$ piece, the $m_{t\bar{t}}$ behaviour for which is quite similar to that for the SM piece. The other parameter space point corresponding to a much smaller value of Λ and the $\mathcal{O}(\rho^2/\Lambda^2)$ piece, which now plays an important role, has a very different $m_{t\bar{t}}$ dependence.

Such distinctions can also be made using other kinematic variables such as transverse momentum and difference in the rapidities of t and $\bar{t}$. However, they do not prove to be any more sensitive than the $m_{t\bar{t}}$ distribution.

4. Summary

In a large class of models, the top quark may have a substantial anomalous chromomagnetic and/or chromoelectric dipole moments. The presence of such moments can lead to sizable deviations in $t\bar{t}$ production cross-sections at hadron colliders. A comparison with the Tevatron data, thus, serves to impose significant constraints on the parameter space. While fortuitous cancellations between different contributions to the total cross-section can serve to allow for sizable values of such couplings, the adoption of the more conservative effective field theory language implies that the Tevatron measurement of $\sigma_{t\bar{t}}$ alone tells that the corresponding new physics scale should be larger than $\sim 7\,\text{TeV}$.

The use of the invariant mass spectrum presents an intriguing prospect. On the one hand, this results in far more severe restriction on the positive values of the chromomagnetic moment. On the other hand, for moderate negative values of the same, the resultant spectrum is found to approximate the CDF data to a better extent than the SM. While it is premature to claim this to be a discovery of a non-zero chromomagnetic dipole moment for the top, it, nevertheless, points to the need of understanding the spectrum better as well as to perform a more detailed analysis.

At the LHC, understandably, it would be possible to probe smaller values of such couplings. However, the improvement is not likely to be a qualitative one (new physics scale $\Lambda \sim 10\,\text{TeV}$) unless the errors on the $t\bar{t}$ cross-sections, both theoretical and experimental, can be reduced significantly. Interestingly, with the relative deviation in the total cross-section (due to new physics) being only very weakly dependent on $\sqrt{s}$, an increase in the accumulated luminosity is likely to lead to better constraints than an increase in the operating energy of the machine. Furthermore, a larger sample size would allow a more detailed use of the differential distributions (such as the $m_{t\bar{t}}$ one), leading to an even more enhanced sensitivity. Indeed, it seems possible that this could even be used to distinguish between different operators that result in identical deviations in the total cross-section.

Note added: As this paper was being finalized, ref. [32] appeared as a preprint. Our expressions are in agreement with those in ref. [32]. Bearing in mind that we use different computational methods, have different choices of parton densities and use different methods to account for NLO effects, our projected cross-sections can also be said to be in reasonable agreement.

While this paper was being reviewed, the ATLAS [33] and the CMS [34] Collaborations announced their measurements of $t\bar{t}$ cross-sections at the LHC. Combining an analysis of $36\,(3)\,\text{pb}^{-1}$ data in the semileptonic (dilepton) decay modes, CMS quotes $\sigma_{t\bar{t}} = [158 \pm 10(\text{stat}) \pm 15(\text{syst}) \pm 6(\text{lumi})]\,\text{pb}$. Similarly, analysing $35\,\text{pb}^{-1}$ data in similar modes, the ATLAS Collaboration has $\sigma_{t\bar{t}} = [180 \pm 9(\text{stat}) \pm 15(\text{syst}) \pm 6(\text{lumi})]\,\text{pb}$. With the approximate next-to-next-to-leading order (NNLO) cross-section, as calculated in ref. [24] being

$$\sigma_{t\bar{t}} = 163^{+7}_{-5}(\text{scale}) \pm 9(\text{PDF})\,\text{pb} = 163^{+11}_{-10}\,\text{pb}\,,$$

both the measurements are in accordance with the SM value, and consistent with each other. It is interesting to note that the combined 2σ experimental uncertainty is already at the 15% mark. Thus, the bounds as derived from this data would already be competitive with those obtained from the Tevatron. However, given the theoretical and experimental uncertainties, we feel that it is still too premature to derive any such stringent and definitive limits.

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