Constraints on Anomalous Top Quark Couplings at the LHC *

Thomas G. Rizzo
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

ABSTRACT

Measurements of distributions associated with the pair production of top quarks at the LHC can be used to constrain (or observe) the anomalous chromomagnetic dipole moment(κ) of the top. For example, using either the $t\bar{t}$ invariant mass or the p_t distribution of top we find that sensitivities to $|\kappa|$ of order 0.05 are obtainable with 100 fb^{-1} of integrated luminosity. This is similar in magnitude to what can be obtained at a 500 GeV NLC with an integrated luminosity of 50 fb^{-1} through an examination of the $e^+e^- \to t\bar{t}g$ process.

I. INTRODUCTION

The Standard Model(SM) has provided a remarkably successful description of almost all available data involving the strong and electroweak interactions. In particular, the discovery of the top quark at the Tevatron with a mass[1], $m_t = 175 \pm 6$ GeV, close to that anticipated by fits to precision electroweak data[2] is indeed a great triumph. However, we know that new physics beyond the SM must exist for many reasons particularly those associated with the fermion mass generating process. Since the top is the most massive fermion, it is believed by many that the detailed physics of the top quark may be significantly different than what is predicted by the SM. In this scenario, the top provides a window into the new physics which lies beyond the electroweak scale. This suggestion makes precision measurements of all of the top quark's properties absolutely mandatory and will require the existence of top quark factories.

One of the most obvious and easily imagined scenarios is one in which the top's couplings to the SM gauge bosons, *i.e.*, the W, Z, γ, and g, are altered. In the case of the electroweak interactions involved in top pair production in e^+e^- collisions, the lowest dimensional gauge-invariant operators representing new physics that we can introduce take the form of dipole moment-type couplings to the γ and Z. In the case of strong interactions, the subject of the present work, the corresponding lowest dimensional operator conserving CP that we can introduce is the anomalous chromomagnetic moment κ[3, 4]. On the otherhand, the corresponding chromoelectric moment, $\tilde{\kappa}$, violates CP. In this modified version of QCD for the top quark the $t\bar{t}g$ interaction Lagrangian takes the form

$$\mathcal{L} = g_s \bar{t} T_a \left(\gamma_\mu + \frac{i}{2m_t} \sigma_{\mu\nu} (\kappa - i\tilde{\kappa}\gamma_5) q^\nu \right) t G_a^\mu \,, \qquad (1)$$

where g_s is the strong coupling constant, m_t is the top quark mass, T_a are the color generators, G_a^μ is the gluon field and q is the outgoing gluon momentum. Due to the non-Abelian nature of QCD, a corresponding four-point $t\bar{t}gg$ interaction, proportional to κ and/or $\tilde{\kappa}$, is by necessity also generated.

Perhaps the most obvious place to probe for anomalous top couplings is at hadron colliders. It is clear that the existence of a non-zero value for κ (and/or $\tilde{\kappa}$) would lead to a modification in *both* the $gg \to t\bar{t}$ and $q\bar{q} \to t\bar{t}$ subprocess cross sections at these machines. The general expressions for these parton level cross sections are given in Atwood *et al.*[3]. Here we note only that the $q\bar{q}$ subprocess has a quadratic κ dependence while that for the corresponding gg subprocess has a quartic dependence on κ. In our discussion of anomalous top couplings at the LHC, we will ignore for brevity the possibility of a non-zero $\tilde{\kappa}$. Obviously, the observation of the CP-violation induced by non-zero $\tilde{\kappa}$ is a more sensitive probe for the anomalous chromoelectric moment of the top than the kinematic distributions we consider below.

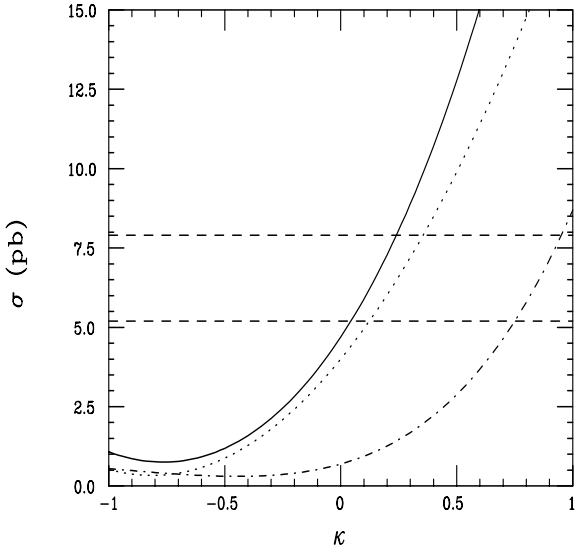

Figure 1: Cross section for $t\bar{t}$ production as a function of κ at the Tevatron for $m_t = 175$ GeV. The dotted(dash-dotted) curve is the $q\bar{q}(gg)$ contribution and the solid line is their sum. MRSA$'$ parton densities were assumed. The horizontal dashed bands correspond to the 1σ world average top pair cross section obtained by CDF and D0.

II. EFFECTS OF ANOMALOUS COUPLINGS

At the Tevatron, it has been shown[3] that for small values of $|\kappa| \leq 0.25$, a range consistent with the current total cross section measurements[1] by both CDF and D0, the dominant effect of anomalous chromomagnetic moment couplings is to

*Work supported by the Department of Energy, contract DE–AC03–76SF00515.

modify the total cross section for top pair production with little influence on the shape of the various distributions. Figure 1 compares the κ-dependent cross section with the world average of that obtained by the CDF and D0 Collaborations.

The essential reason why the various top quark kinematical distributions are not much influenced is that top pair production at the Tevatron is dominated by the invariant mass region near threshold. Since, as is well known, the effects of anomalous couplings grow with the parton center of mass energy one sees little influence at these energies. The significantly larger partonic center of mass energies accessible at the LHC allows us to probe beyond this threshold region so that much higher sensitivities to a possible non-zero κ can be obtained. This is particularly true for the various kinematic distributions.

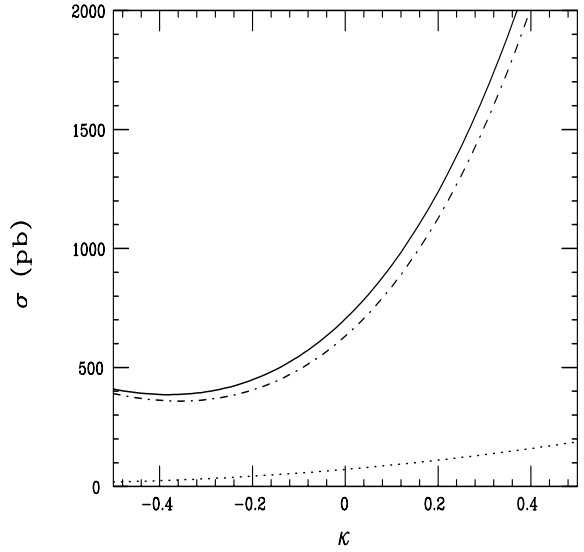

Figure 2: Cross section for $t\bar{t}$ production as a function of κ at the LHC for $m_t = 180$ GeV. The dotted(dash-dotted) curve is the $q\bar{q}(gg)$ contribution and the solid line is their sum. MRSA$'$ parton densities were assumed.

As a result of the subprocess dependencies on κ it is clear than any of the (unnormalized!) differential distributions for a generic observable, $\mathcal{O}$, can then be written as

$$\frac{d\sigma}{d\mathcal{O}} = \sum_{n=0}^{4} \kappa^n g_n(\mathcal{O}) \qquad (2)$$

where $g_n(\mathcal{O})$ are a set of calculable functions which have been completely determined to lowest order in QCD by Atwood *et al.*[3]. The QCD/SM result is just the familiar term with $n = 0$. Of course, the *total* cross section is also a quartic polynomial in κ. The behaviour of the two individual contributing subprocess as well as the total cross sections under variations of κ at the LHC are shown in Fig. 2. Unlike the Tevatron, the gg initial state dominates the top pair production cross section at the LHC. A reasonable sensitivity to κ is again observed in the total cross section as it was for the Tevatron. However, as discussed in Ref.[3], unless the theoretical and systematic uncertainties are well under control, a measurement of $\sigma_{t\bar{t}}$ at the LHC will never do much better than to constrain $|\kappa| \leq 0.10 - 0.15$. To further improve on this limit we must turn to the various top quark kinematical distributions.

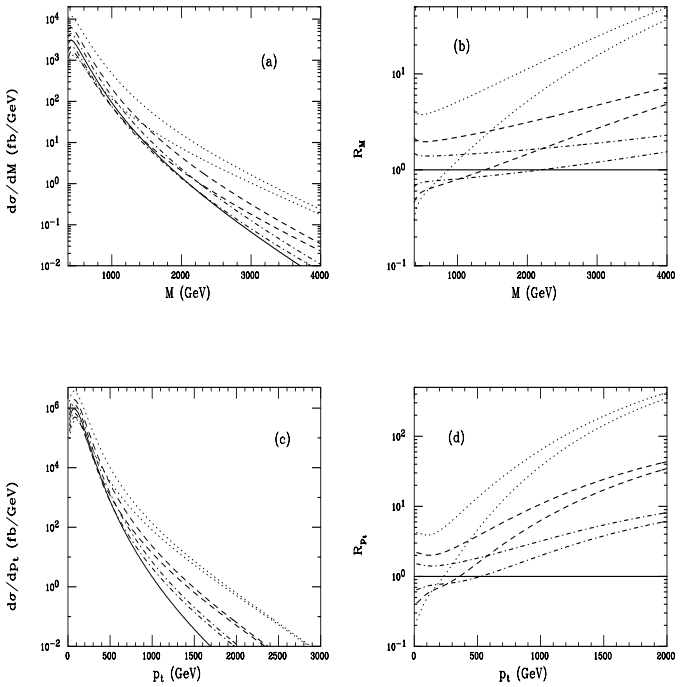

Figure 3: (a) $t\bar{t}$ invariant mass distribution at the LHC for various values of κ assuming $m_t = 180$ GeV. (b) The same distribution scaled to the SM result. (c) $t\bar{t}$ p_t distribution at the LHC and (d) the same distribution scaled to the SM. In all cases, the SM is represented by the solid curve whereas the upper(lower) pairs of dotted(dashed, dash-dotted) curves corresponds to κ =0.5(-0.5), 0.25(-0.25), and 0.125(-0.125), respectively.

III. ANALYSIS

As has been shown elsewhere[3], the p_t and pair invariant mass (M_{tt}) distributions for top quark pair production at the LHC are highly sensitive to non-zero values of κ. Figures 3a and 3c show the modifications in the SM expectations for both $d\sigma/dM_{tt}$ and $d\sigma/dp_t$, respectively, for different values of κ. Perhaps more revealingly, Figures 3b and 3d show the ratio of the modified distributions to the corresponding SM ones. We see the important results that a non-zero κ leads to (i) enhanced cross sections at large p_t and M_{tt} and (ii) the *shapes* of the distributions are altered, *i.e.*, the effect is not just an overall change in normalization. This is contrary to what was observed in the Tevatron case where both $d\sigma/dM_{tt}$ and $d\sigma/dp_t$ were essentially just rescaled by the ratio of the total cross sections. Clearly, data on these two distributions at the LHC can lead to significant constraints on κ or observe a non-zero effect if κ is sufficiently large. In Ref. [3], the $cos\theta^*$ and rapidity(η) distributions were also examined but they were found to be less sen-

sitive to non-zero κ than the dramatic effects shown in Fig. 3.

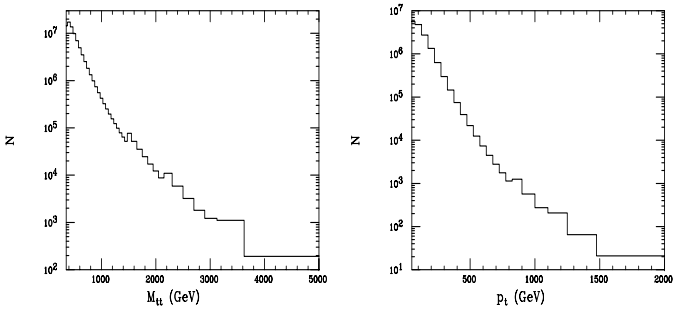

Figure 4: Sample histograms of top quark data generated for the LHC, assuming 100 fb^{-1} of integrated luminosity. On the left(right) is the top pair invariant mass (p_t) distribution. MRSA$'$ parton densities and $m_t = 175$ GeV have been assumed.

How sensitive are these distributions to non-zero κ and what bounds can be obtained at the LHC? In order to answer these questions, we follow a Monte Carlo approach. We begin by generating 100 fb^{-1} `data' samples for both distributions *assuming* the SM is correct. To be specific, since the next to leading order(NLO) expressions for these distributions in the presence of anomalous couplings do not yet exist, we use the leading order results rescaled by the NLO/LO cross section ratios for both subprocesses as effective K-factors to obtain a rough estimate of these higher order effects. Sample histograms of this appropriately rescaled `data' are shown in Fig. 4. Note that there are 37 bins in M_{tt} and 22 bins in p_t of varying sizes essentially covering the entire kinematically allowed ranges. Bin sizes are adjusted to partially conform to changes in resolution and declining statistics as we go to larger values of either kinematic variable. In addition to the usual statistical errors, we attempted to include some estimate of the systematic point-to-point errors. These were added in quadrature to the statistical errors. Thus, neglecting the overall normalization uncertainties, the error in the number of events(N_i) in a given bin(i) was assumed to be given by

$$\delta N_i = [N_i + aN_i^2]^{1/2} \tag{3}$$

with the parameter a setting the *a priori* unknown size of the systematic error. Note that we have made the simplifying assumption that the magnitude of a is bin independent. The total error is thus generally systematics dominated. With these errors the Monte Carlo generated data was then fit to the known functional form of the relevant distribution:

$$\frac{d\sigma}{d\mathcal{O}} = f \sum_{n=0}^{4} \kappa^n g_n(\mathcal{O}) \tag{4}$$

where f allows the overall normalization to float in the fit and the g_n were those appropriate to either the p_t or M_{tt} distributions.

The results of this analysis are thus a set of 95% CL allowed regions in the $f - \kappa$ plane for various assumed values of the anticipated size of the systematic errors. These can be seen in Figure 5. Here we see that for systematic errors of reasonable magnitude the value of κ is constrained to lie in the range $-0.09 \leq \kappa \leq 0.10$ from the M_{tt} distribution and $-0.06 \leq \kappa \leq 0.06$ from the corresponding p_t distribution. Note that the correlation between f and κ is much stronger in the case of the M_{tt} distribution. Increasing the integrated luminosity by a factor of two will not greatly affect our results since the errors are systematics dominated. Combining the results of multiple distributions in a global fit to κ will most likely result in even strong bounds.

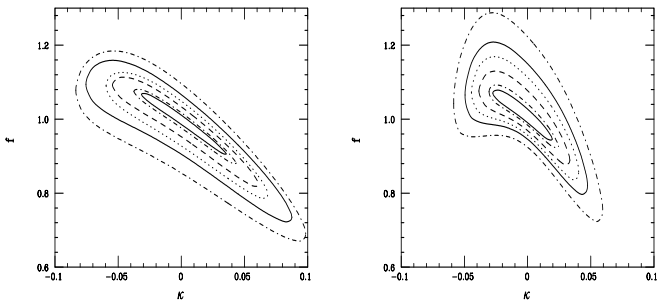

Figure 5: 95% CL two parameter (f, κ) fits to the invariant mass(left) and p_t(right) distributions at the LHC for a 175 GeV top quark assuming the MRSA$'$ parton densities for different assumed values of the systematic errors parameterized by a. From inside out the curves correspond to a= 0.03, 0.05, 0.10, 0.15, 0.20, and 0.30, respectively.

Using Figure 6 we can make a direct comparison of the bounds obtainable on κ at the NLC by using the process $e^+e^- \to t\bar{t}g$ as discussed in Ref.[4] with those from the LHC analysis above. In these Figures the influence of $\tilde{\kappa}$ is also shown. These NLC results were obtained by fitting the spectrum of very high energy gluon jets produced in association with top pairs (above some cut, E_g^{min}, used to avoid contamination from the radiation off final state b-quarks in top decay). Only statistical errors were included in the analysis. The resulting bounds are essentially statistics limited. We see from these Figures that the constraints on κ from the $\sqrt{s}$=500 GeV NLC with an integrated luminosity of 50 fb^{-1} are only slightly better than what is achievable at the LHC from the top pair's p_t distribution. The constraints tighten at the 1 TeV NLC. Clearly the LHC and NLC have comparable sensitivities to the anomalous chromomagnetic moment of the top.

IV. ACKNOWLEDGEMENTS

The author would like to thank J. Hewett, A. Kagan, P. Burrows, L. Orr, and R. Harris for discussions related to this work.

V. REFERENCES

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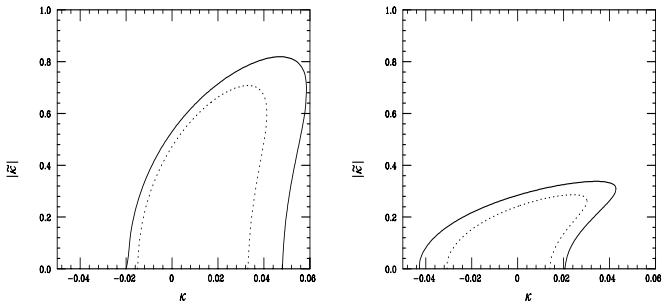

Figure 6: 95% CL allowed regions in the $\kappa - \tilde{\kappa}$ plane obtained from fitting the gluon spectrum. On the left the fit is for gluon jets above E_g^{min}=25 GeV at a 500 GeV NLC assuming an integrated luminosity of 50(solid) or 100(dotted) fb^{-1}. On the right is the case of a 1 TeV collider with E_g^{min}=50 GeV and luminosities of 100(solid) and 200(dotted) fb^{-1}. Note that the allowed region has been significantly compressed downward in comparison to the 500 GeV case.

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