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Anomalous Chromoelectric and Chromomagnetic Moments of the Top Quark at the NLC

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ABSTRACT

The production of top quark pairs in association with a hard gluon in e^+e^- collisions at the NLC provides an opportunity to probe for anomalous $t\bar{t}g$ couplings, *e.g.*, the chromoelectric and chromomagnetic moments of the top. We demonstrate that an examination of the energy spectrum of the additional gluon jet can yield strong constraints on the size of these two anomalous couplings. The results are shown to be quite sensitive to the cut on the minimum gluon jet energy needed to remove events where the final state b-quark radiates strongly. The possibility of using additional observables to improve the sensitivity to anomalous couplings is briefly discussed.

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1 Introduction

The discovery of the top quark with a mass consistent with the expectations from precision electroweak measurements is a major triumph for the Standard Model(SM). However, due to the fact that it is so heavy, $m_t = 175 \pm 9$ GeV[1], the top itself has been proposed as a window for new physics *beyond* the SM. One obvious scenario is a modification of the interactions of the top quark with the conventional gauge bosons, *i.e.*, the W, Z, γ, and g, whose couplings to top may differ in detail from those anticipated by the SM. This possibility has lead to a substantial effort over the past few years[2] investigating potential anomalous couplings of the top as well as other third generation fermions. In the case of the strong interactions of the top, the lowest dimensional gauge-invariant operator representing new top quark physics and conserving CP that we can introduce is the anomalous chromomagnetic moment, which we can parameterize via a dimensionless quantity κ. On the otherhand, the corresponding chromoelectric moment, parameterized by $\tilde{\kappa}$, violates CP and arises from an operator of the same dimension. In this modified version of QCD for the top quark, the tree-level three-point $t\bar{t}g$ interaction Lagrangian takes the form

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

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 four-point, dimension-five $t\bar{t}gg$ interaction is also generated, but this will not concern us in the present work since it only contributes to the process of interest at higher order. As has been discussed in the literature, if either or both of $\kappa, \tilde{\kappa}$ are sufficiently large in magnitude their effects can be probed through top pair production processes at both e^+e^-[3] and hadron[4] colliders. The purpose of the present work is to consider the sensitivity of $t\bar{t}g$ production in e^+e^- collisions at the NLC to non-zero values of κ and $\tilde{\kappa}$.

2 Analysis

In our analysis we will only consider how the top quark anomalous couplings can modify the energy distribution of the extra gluon jet associated with top pair production. In principle, other observables may be available that are also sensitive to these couplings; these are generally beyond the scope of the present work, but one example will be discussed later. The basic cross section formulae and analysis procedure can be found in Ref.[3]. Here, we go beyond this initial study in several ways: (i) we generalize the form of the $t\bar{t}g$ coupling to allow for the possibility of a sizeable chromoelectric moment, $\tilde{\kappa}$. The incorporation of $\tilde{\kappa} \neq 0$ into the expressions for the differential cross section in Ref.[3] is rather straightforward and can be accomplished by the simple substitution $\kappa^2 \to \kappa^2 + \tilde{\kappa}^2$ made universally. Note that since a non-zero value of $\tilde{\kappa}$ produces a CP-violating interaction it appears only quadratically in the expression for the gluon energy distribution since this is a CP-conserving observable. Thus, in comparison to κ, we anticipate a greatly reduced sensitivity to the value of

$\tilde{\kappa}$. (ii) We use updated expectations for the available integrated luminosities of the NLC at various center of mass energies as well as an updated efficiency($\simeq$ 100%) for identifying top-quark pair production events. Both of these changes obviously leads to a direct increase in statistical power compared to Ref.[3] (iii) We lower the cut placed on the minimum gluon jet energy, E_g^{min}, in performing the energy spectrum fits. The reasons for having such a cut are two-fold. First, a minimum gluon energy is required to identify the event as $t\bar{t}g$. The cross section itself is infra-red singular though free of co-linear singularities due to the finite top quark mass. Second, since the top decays rather quickly, $\Gamma_t \simeq 1.45$ GeV, we need to worry about 'contamination' from the additional gluon radiation off of the b-quarks in the final state. Such events can be effectively removed from our sample if we require that $E_g^{min}/\Gamma_t >> 1$. In our past analysis we were overly conservative in our choices for E_g^{min} in order to make this ratio as large as possible, *i.e.*, we assumed $E_g^{min} = 50(200)$ GeV for an NLC with a center of mass energy of 500(1000) GeV. It is now believed that we can with reasonable justification soften these cuts to at least as low a value as 25(50) GeV for the same center of mass energies[5], with a potential further softening of the cut at the higher energy machine being possible. Due to the dramatic infra-red behaviour of the cross section, this change in the cuts leads not only to an increased statistical power but also to a longer lever arm to probe events with very large gluon jet energies which have the most sensitivity to the presence of anomalous couplings. Combining all these modifications, as one might expect, we find constraints which are substantially stronger than what was obtained in our previous analysis[3].

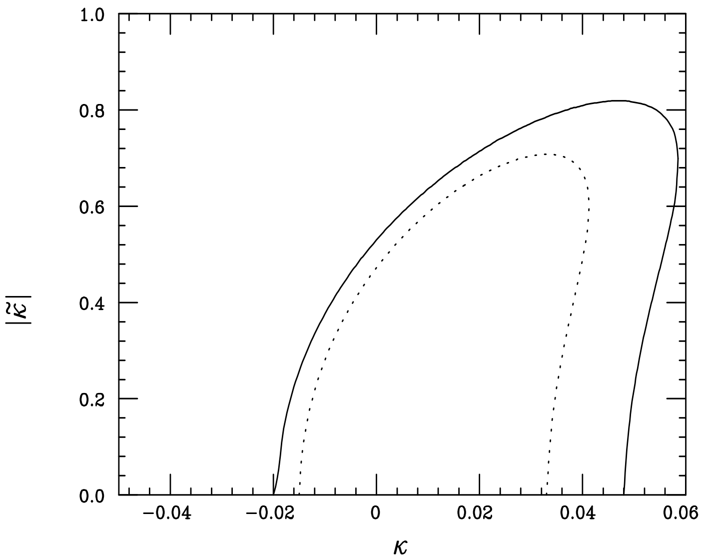

Figure 1: 95% CL allowed region in the $\kappa - \tilde{\kappa}$ plane obtained from fitting the gluon spectrum above E_g^{min}=25 GeV at a 500 GeV NLC assuming an integrated luminosity of 50(solid) or 100(dotted) fb^{-1}.

As in Ref.[3], our analysis follows a Monte Carlo approach employing statistical errors only. For a given e^+e^- center of mass energy, a binned gluon jet spectrum is generated for energies above E_g^{min} assuming that the SM is correct. The bin widths are fixed to be $\Delta z = 0.05$ where $z = 2E_g/\sqrt{s}$ for all values of $\sqrt{s}$, with the number of bins thus determined by the values of the top mass(m_t=175 GeV), $\sqrt{s}$ and E_g^{min}. All calculations are performed only in the lowest order. As an example, at a 500 GeV NLC with E_g^{min}=25 GeV, there are 8 energy bins for the gluon energy spectrum beginning at $z = 0.10$; the last bin covers the range above $z = 0.45$. After the Monte Carlo data samples are generated, we perform a fit to the general expressions for the $\kappa - \tilde{\kappa}$ dependent spectrum and obtain the 95% CL allowed region in the $\kappa - |\tilde{\kappa}|$ plane. (Note that only the absolute value of $\tilde{\kappa}$ occurs due to the reasons described above.)

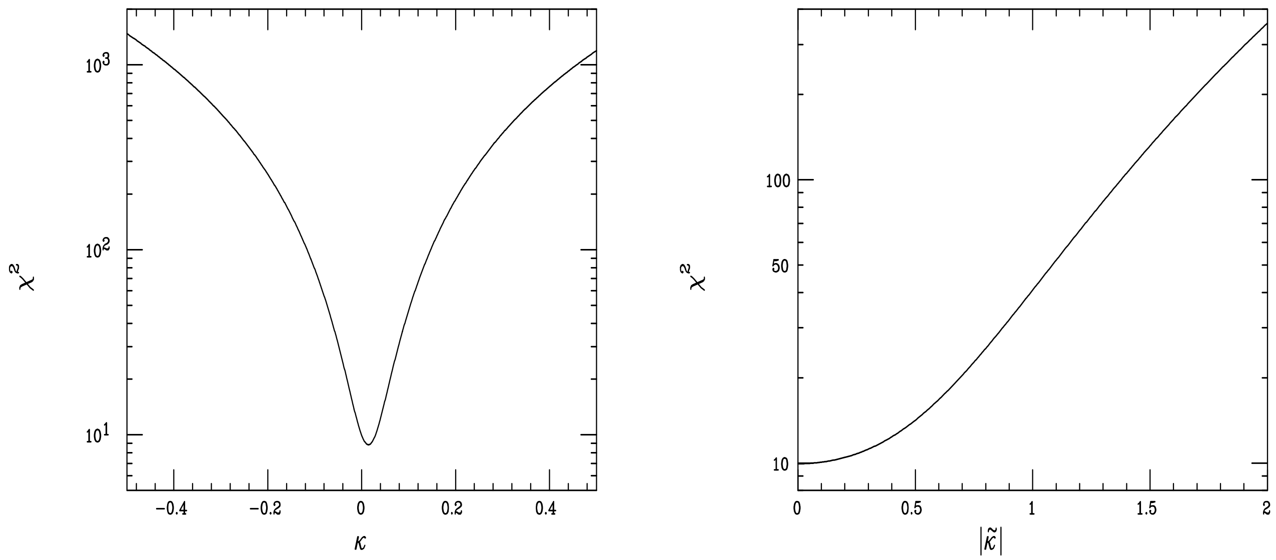

Figure 2: χ^2 plots for the 500 GeV NLC with a luminosity of 50 fb^{-1} corresponding to Fig. 1. Only one of κ or $\tilde{\kappa}$ is assumed to be non-zero at a time.

Fig. 1 shows the results of this procedure for a 500 GeV NLC with a cut of E_g^{min}=25 GeV for two different integrated luminosities. As expected, excellent constraints on κ are now obtained but those on $\tilde{\kappa}$ are more than an order of magnitude weaker. A doubling of the integrated luminosity from 50 to 100 fb^{-1} decreases the size of the allowed region by about 40%. We note that in the previous study only extremely poor constraints on κ were obtained at a 500 GeV e^+e^- collider, $-1.98 \leq \kappa \leq 0.44$, due to the presence of a degenerate minima in the χ^2 distribution. Now, with the both the increased luminosity and top-tagging efficiencies, as well as the longer lever arm in energy, these previous difficulties are circumvented. This is explicitly shown by the χ^2 plots in Fig. 2. In the case of a non-zero

κ a very sharp minimum is found whereas the rise in χ^2 is slow when $\tilde{\kappa}$ is non-zero. In neither case is there any evidence for a second minimum. This lack of degeneracy is found to hold for all the other cases we have considered.

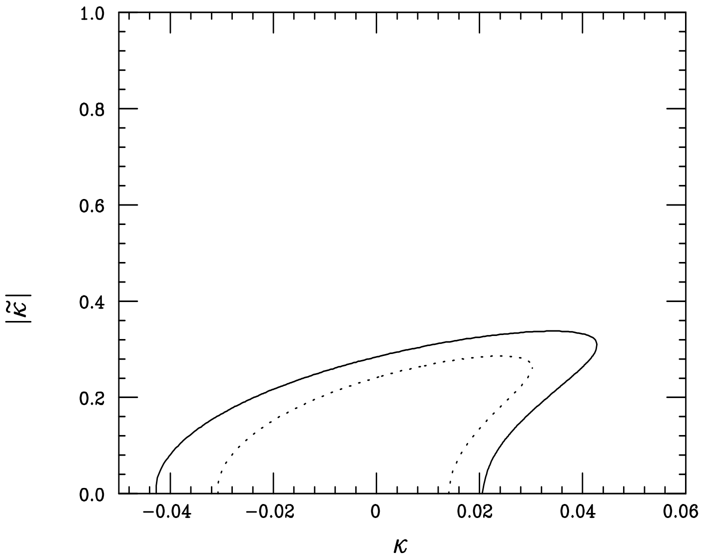

Figure 3: Same as Fig. 1, but for a 1 TeV collider with E_g^{min}=50 GeV and luminosities of 100(solid) and 200(dotted) fb^{-1}. Note that the allowed region has been significantly compressed downward in comparison to Fig. 1.

Going to a higher energy leads to several simultaneous effects. First, since the cross section approximately scales like $\sim 1/s$ apart from phase space factors, a simple doubling of the collider energy induces a reduction in statistics unless higher integrated luminosities are available to compensate. Second, the sensitivity to the presence of non-zero anomalous couplings is enhanced at higher energies, roughly scaling like $\sim \sqrt{s}$ for κ and, correspondingly, like $\sim s$ for $\tilde{\kappa}$ *assuming* the same available statistics at all energies. In Fig. 3 we show the results of our analysis at a 1 TeV NLC for E_g^{min}=50 GeV; the corresponding case where we maintain the jet energy cut of E_g^{min}=25 GeV is shown in Fig. 4. (Note that in our previous analysis, we obtained the 95% CL bound $-0.12 \leq \kappa \leq 0.21$ for this center of mass energy and an integrated luminosity of 200 fb^{-1}.) For E_g^{min}=50(25) GeV, the energy range is divided into 15(16) $\Delta z = 0.2$ bins beginning at $z = 0.10(0.05)$ with the last bin covering the range $z \geq 0.80$. We see from these figures that by going to higher energy we drastically compress the allowed range of $\tilde{\kappa}$ while the improvement for κ is not as great. Lowering the energy cut is seen to lead to a far greater reduction in the size of the 95% CL allowed region than is a simple doubling of the integrated luminosity. This demonstrates that if improvements to the present analysis are to be made it is very important to explore just how low the E_g^{min} can be placed and still remove the contamination from gluon radiation off of final state b-quarks.

Comparing the 200 fb^{-1} result in Fig. 4 with the corresponding case of 50 fb^{-1} in Fig. 1, we see that our approximate scaling laws are observed to hold rather well.

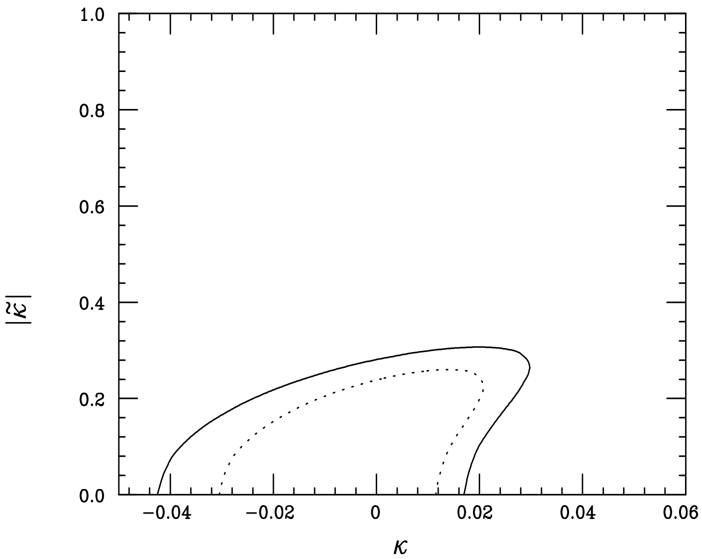

Figure 4: Same as Fig. 3 but with E_g^{min} = 25 GeV.

As a final example, we consider a $\sqrt{s}$=1.5 TeV NLC with E_g^{min}=75 GeV. This requires 16 Δz = 0.05 bins beginning at z = 0.10 to cover the entire gluon jet energy spectrum; the final bin covers the range $z \geq 0.85$. The results of this analysis are shown in Fig. 5 assuming integrated luminosities of 200 and 300 fb^{-1}. The 95% CL allowed region is seen to be further compressed in the vertical direction, *i.e.*, to smaller values of $\tilde{\kappa}$, than that found in the 1 TeV NLC case with either E_g^{min}=25 or 50 GeV. However, the overall size of the allowed region for the 1.5 TeV collider with E_g^{min} =75 GeV is comparable to that of the 1 TeV NLC with E_g^{min} =25 GeV. Softening the E_g^{min} cut at the 1.5 TeV collider will yield even stronger constraints.

3 Discussion and Conclusions

We have presented an updated analysis of the constraints imposed on the chromoelectric and chromomagnetic moments of the top quark by detailed measurements of the gluon jet energy spectrum associated with the process $e^+e^- \rightarrow t\bar{t}g$ at the NLC for various center of mass energies. The value of the cut on the gluon energy was shown to play a key role in obtaining strong bounds on these anomalous couplings. These results may be strengthened in the future if we find that the E_g^{min} cut can be further softened.

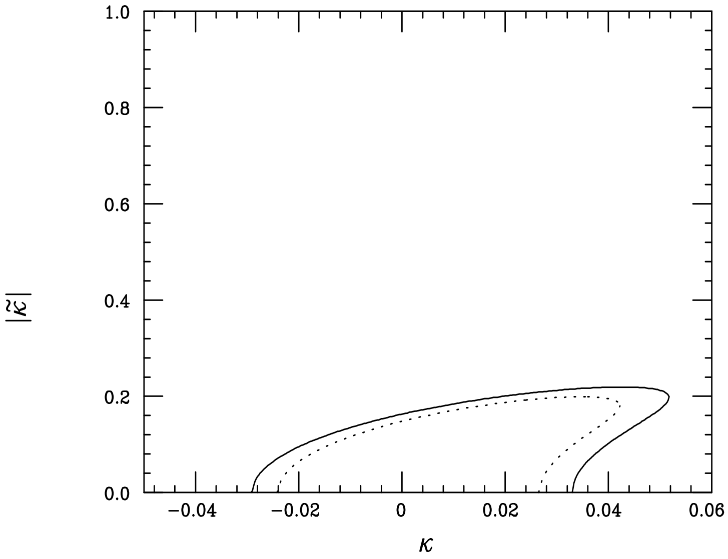

Figure 5: Same as Fig. 1 but for a 1.5 TeV NLC with E_g^{min}=75 GeV for luminosities of 200(solid) and 300(dotted) fb^{-1}.

If we are to improve the sensitivity to anomalous couplings we must introduce additional observables. The large initial electron beam polarization, $P = 90\%$, may play an important role in this regard. To get an idea of how this might work, we can construct an asymmetry using the Monte Carlo data generated above by asking how the number of events in a fixed energy bin is altered when one changes from left-handed to right-handed polarization, *i.e.*, $A(z) = [N_L(z) - N_R(z)]/[N_L(z) + N_R(z)]$. For a $\sqrt{s}$=500 GeV NLC, A is found to be approximately z independent with a value near 39% in the SM and will in general be $\kappa, \tilde{\kappa}$ dependent if anomalous couplings are present. We thus can repeat our analysis for the 500 GeV case now including the values of A in the fit. This is shown in Fig. 6. Unfortunately including A has not drastically reduced the size of the 95% CL allowed region as we might have hoped since A is only rather weakly dependent on the anomalous couplings. Thus we must seek out other observables, particularly those which are sensitive to the CP-violating chromoelectric moment interactions. This analysis is currently underway.

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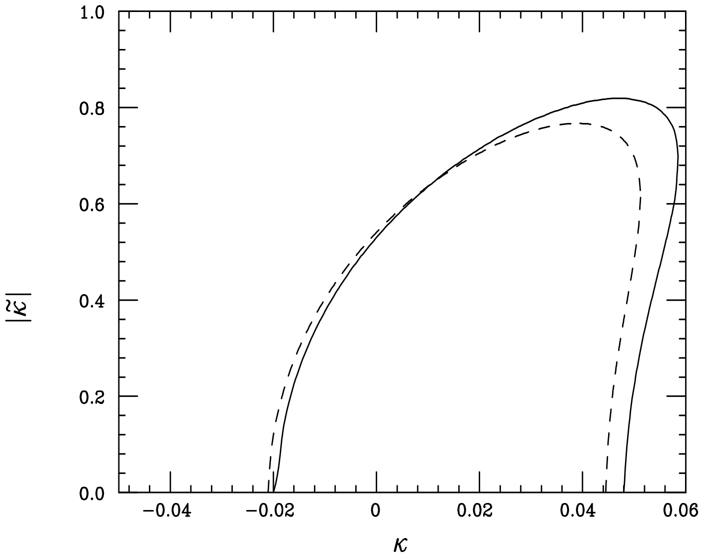

Figure 6: The solid curve is the same as in Fig. 1 for a 500 GeV NLC with E_g^{min}=25 GeV and a luminosities of 50 fb^{-1}. The dashed curve included the polarization asymmetry into the fit assuming an initial beam polarization of 90%.

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