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Constraining Anomalous Top Quark Couplings at the Tevatron *

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Abstract

We explore the influence of an anomalous chromomagnetic moment, κ, on the production characteristics of top quark pairs at the Tevatron. We find that for top quarks in the 170 GeV mass range, present searches are probing values of κ of order $\frac{1}{3}$. For κ's in this range we find that significant enhancements in the both the $q\bar{q},\ gg \to t\bar{t}$ production cross sections are obtained. Once top has been verified and QCD uncertainties are under control, future high statistics measurements at the Tevatron will eventually be sensitive to values of κ with magnitudes smaller than 0.10-0.15. We discuss a class of scalar technicolor models which may produce large values of κ in conjunction with generation of m_t.

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The possible discovery of the top quark at the Tevatron by the CDF Collaboration[1, 2] in the mass range anticipated by precision electroweak data[3] represents a great triumph for the Standard Model(SM). Once confirmed, a detailed study of the nature of the top (*e.g.*, width, couplings, production properties) at both hadron[4] and e^+e^-[5] colliders may yield significant information on new physics which lies somewhere beyond current energy scales. Existing indirect constraints on several of the top's properties from low energy data are relatively poor[6] and leave plenty of room for new physics. At the present time the CDF and D0 results seem to be *roughly* in accord with the expectations of QCD[7]. However, the cross section as determined by CDF does appear to be somewhat above the SM prediction which has prompted much theoretical speculation[8] as to new dynamics which may be present. This is shown explicitly in Figure 1 which compares the data from both the CDF and D0 Collaborations with the most recent theoretical next-to-leading order(NLO) calculations which include gluon resummation. A well established difference between the predictions of QCD and the Tevatron experiments would indicate the presence of new physics. If the source of this new physics is at the TeV scale then the leading effect should be parameterized my a QCD chromomagnetic dipole moment since this is the lowest dimension CP-conserving effective Lagrangian contributing to the gluon-top coupling.

In this paper we will consider the possibility that the top quark possesses a non-zero anomalous chromomagnetic dipole moment, κ, in its coupling to gluons and explore the implications of such a scenario for top pair production at the Tevatron. To get an idea of how large κ might be due to new physics one notes that if the gluon is removed from a chromomagnetic dipole moment graph one is often left with a finite contribution to the top mass. If this is the origin of the top mass dimensional analysis implies that κ is $\mathcal{O}\left(\frac{m_t^2}{\Lambda^2}\right)$, where Λ is the scale of new physics. As we'll see, this suggests that there is new physics below a TeV if there is a substantial increase in the $t\bar{t}$ production cross-section due to non-zero κ.

Chromomagnetic dipole moments in association with quark mass generation can occur quite naturally in composite models and in technicolor models. Following a phenomenological discussion we will describe a class of scalar technicolor models[9, 10] in which it may be possible to obtain $\kappa \sim \frac{1}{4}$, resulting in an $\mathcal{O}(50\%)$ increase in the $t\bar{t}$ production cross section at the Tevatron.

To begin our analysis, we consider the piece of the Lagrangian which governs the $t\bar{t}g$ coupling:

$$\mathcal{L} = g_s \bar{t} T_a \left(\gamma_\mu + i \frac{F_2}{2m_t} \sigma_{\mu\nu} q^\nu \right) t G_a^\mu \,, \tag{1}$$

where g_s and T_a are the usual $SU(3)_c$ coupling and generators, m_t is the top quark mass, q is the gluon momentum, and F_2 represents a q^2-dependent form factor. For $|q^2| << \Lambda^2$, the intrinsic scale in the form factor, we define $F_2 = \kappa$ following the usual notation. In order to examine the effects of non-zero κ on $t\bar{t}$ production, we must first calculate the parton-level $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ differential cross sections. For the $q\bar{q}$ case we obtain[13]

$$\frac{d\sigma_{q\bar{q}}}{d\hat{t}} = \frac{2\pi\alpha_s^2}{27\hat{s}^2} \left[\left(1 + \frac{2m_t^2}{\hat{s}} \right) + 3F_2 + F_2^2 \left(\frac{\hat{s}}{8m_t^2} + 1 \right) + \frac{1}{4}(3z^2 - 1) \left(1 - \frac{\hat{s}}{4m_t^2} F_2^2 \right) \right] \,, \tag{2}$$

with $\hat{s}$ being the parton level center of mass energy and z being the cosine of the corresponding scattering angle, θ^*, as defined via the usual relations

$$\begin{aligned} \hat{t} &= \frac{-\hat{s}(1-\beta z)}{2} + m_t^2 \,, \\ \hat{u} &= \frac{-\hat{s}(1+\beta z)}{2} + m_t^2 \,, \end{aligned} \tag{3}$$

with $\beta = (1 - 4m_t^2/\hat{s})^{1/2}$. In this expression, F_2 is evaluated at $q^2 = \hat{s}$; note the quadratic dependence on F_2. Since top quark pair production at Tevatron for masses near 170 GeV is dominated by the threshold region of the $q\bar{q}$ annihilation process(at least for $\kappa = 1$), a brief discussion of the influence of finite F_2 on the parton level process is relevant. For $\hat{s} \simeq 4m_t^2$, we see that F_2 has two important effects on the differential cross section: (i) the angular dependence is softened and (ii) the total cross section has a minimum at $F_2 = -1/2$ and grows rapidly as F_2 increases in a positive manner away from zero. For example, the near-threshold cross section for $F_2 = 0.5$ is 2.5 times larger than for $F_2 = 0$. We expect these qualitative results to be maintained even after folding with the parton distributions and all integrations are performed as will be verified by explicit calculation below.

In ordinary LO and NLO QCD, for top quarks in the mass range of interest, one finds that the $q\bar{q} \to t\bar{t}$ subprocess contributes almost 90% of the entire cross section. As we will see below, the dominance of this process remains even when κ is non-zero provided it's magnitude is not too large, say, $\kappa < 1$. It is thus worth while to briefly explore the influence of F_2 with Λ finite on the LO $q\bar{q} \to t\bar{t}$ subprocess. To do this, we simply fold the above differential distribution with the structure functions of the CTEQ Collaboration[14] thus obtaining the results presented in Figure 2. We assume for these results that F_2 can be simply expressed in the simple form

$$F_2 \quad = \quad \kappa(1 + \frac{\hat{s}}{\Lambda^2})^{-1} \,, \tag{4}$$

at least as a first approximation. We see immediately that once Λ approaches 1-2 TeV there is not much influence from Λ being finite as expected from the discussion above. The reason for this is the fact that most of the weight of the subprocess cross section comes from the threshold region. For simplicity, we will take Λ to infinity in our phenomenological calculations below. The sensitivity of the LO $q\bar{q} \to t\bar{t}$ subprocess to finite κ is clearly demonstrated by this figure as we see that the cross section scales by factors of order 5-10 as κ varies between 1 and -1. This sensitivity will persist in the more detailed calculations below.

The case of the $gg \to t\bar{t}$ differential cross section is much more complicated; let us for simplicity consider the limit where $\Lambda >> \hat{s}$ so that we can make the replacement $F_2 \to \kappa$. Even in this 'simpler' situation, we must add an additional, dimension-5, four-point $t\bar{t}gg$ interaction proportional to κ to maintain gauge invariance[15]. Defining the kinematic abbreviations

$$\begin{aligned} x &= \frac{m_t^2}{\hat{s}}\,, \\ K &= \frac{\kappa}{2\sqrt{x}}\,, \\ d &= 1 - z^2 + 4xz^2\,, \end{aligned} \tag{5}$$

the resulting differential cross section can be written as

$$\frac{d\sigma_{gg}}{d\hat{t}} = \frac{\pi\alpha_s^2}{64\hat{s}^2}\left[T_0 + T_1 K + T_2 K^2 + T_3 K^3 + T_4 K^4\right]\,, \tag{6}$$

a quartic polynomial in κ, where the T_i can be written as

$$\begin{aligned} T_0 &= 4(36xz^2 - 7 - 9z^2)(z^4 - 8xz^4 + 16x^2z^4 - 32x^2z^2 + 8xz^2 - 8x - 1)/3d^2\,, \\ T_1 &= -32(36xz^2 - 7 - 9z^2)\sqrt{x}/3d\,, \\ T_2 &= -16(72x^2z^2 - 46xz^2 + 7z^2 - 16x - 7)/3d\,, \\ T_3 &= 32(-7z^2 + 28xz^2 - 5x + 7)\sqrt{x}/3d\,, \\ T_4 &= 16(-8xz^4 + 16x^2z^4 + z^4 - 4x^2z^2 + 9xz^2 - 2z^2 + 1 - x + 4x^2)/3d\,. \end{aligned} \tag{7}$$

This result is easily seen to reduce to the more conventional one when $\kappa \to 0$. One might expect that the sensitivity of the $gg \to t\bar{t}$ differential cross section may be somewhat greater than the $q\bar{q}$ case since it is a quartic function of κ. As in the $q\bar{q}$ case, near threshold the $gg \to t\bar{t}$ cross section increases as κ increases in the positive direction. For $\kappa = 0.5$, the cross section is more than twice as large as what one finds for $\kappa = 0$. When finite Λ corrections become important the calculation of the $gg \to t\bar{t}$ cross section becomes even more intricate since the form factors would then be evaluated at $q^2 = 0$ in the $\hat{t}-$ and $\hat{u}-$exchange diagrams but at $q^2 = \hat{s}$ in both the s-channel and four-point diagrams. The fact that different scales are involved results in a further violation of $SU(3)_c$ gauge invariance because delicate gauge cancellation are no longer taking place. To cure this new problem we need to add an *additional* four- point interaction, as was discussed in Ref.[15], whose contribution to the amplitude is proportional to the difference $F_2(\hat{s}) - F_2(0)$. Since the cross section is dominated by the threshold region and we are working in the large Λ limit, these additional contributions to the $gg \to t\bar{t}$ amplitude can be ignored. Indeed, since the gg contributions to $t\bar{t}$ production remain sub-leading in comparison to those from $q\bar{q}$ for top masses in the 170 GeV range and values of κ of interest to us, we will set $F_2(\hat{s}) = F_2(0) = \kappa$ in the gg contribution in what follows.

To proceed further, we follow Ref.[7] and include NLO and gluon resummation corrections; note that these are the *conventional* QCD corrections and not the additional κ-dependent ones that can arise in higher order. Our philosophy will be to treat the new κ-dependent terms in LO only and include just the SM NLO corrections in the analysis below. Putting this all together we arrive at Figure 3 which shows the separate contributions of the $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ subprocesses as well as their sum in comparison the both the CDF and D0 results as a function of κ. Here we see explicitly some of the general features discussed above: (*i*) For $\kappa > (<) 0$, the cross section is larger(smaller) than the SM prediction; (*ii*) for $\kappa \neq 0$, the relative weights of the gg and $q\bar{q}$ subprocesses are altered although $q\bar{q}$ remains dominant for $\kappa > 0$. For $-1 \leq \kappa \leq -0.5$ we see that both contributions are small and have comparable magnitudes. (*iii*) To increase the total cross section to near the result found by CDF (and still be consistent with the D0 bound) would require values of κ in the approximate range $1/4 - 1/3$. Certainly, negative values of κ are not favored by the existing data; clearly, new top production cross section determinations from both the CDF and D0 collaborations are eagerly awaited.

If the top cross section eventually settles down to its SM value, we can use the results in Fig. 3 to place limits on the value of κ. Of course, there are many sources of both theoretical and experimental error which play important roles in determining the resulting allowed κ range. On the theoretical side, one has to deal with (a) scale ambiguities, (b) variations in parton densities, and (c) NNLO corrections; the size of these uncertainties we can estimate from the literature. Laenen *et al.*[7] provide us with an estimate of the uncertainty in the total cross section due to various scale choices: $+14.5\%, -8.6\%$, for tops in the mass range of interest. In a recent paper, Martin, Stirling and Roberts(MRS)[16] have discussed the variation in the $t\bar{t}$ production cross section at the Tevatron with the choice of (modern) parton densities(PD). From their analysis, and the fact that top pairs are dominantly produced at large x, we see that the PD uncertainty is rather small with the variations in the central value of the top cross section being of order $2 - 3\%$. In order to estimate the potential size of the NNLO corrections, we compare the MRS NLO result with that given by Laenen *et al.*, which includes gluon resummation for the same choice of PD. This yields an additional 4% uncertainty to the cross section. If we combine these theoretical errors with the overall scale error due to the Tevatron luminosity as determined by CDF[1] of 3.6%, we arrive at a total uncertainty of $+15.6\%, -10.3\%$. To get a quasi-estimate of the experimental uncertainty, we assume that all of the error, from both statistics and systematics(apart from the luminosity), scales with the increase in statistics; this yields an error of $(+43.3, -34.3)\sqrt{19.3/\mathcal{L}}$, with $\mathcal{L}$ being the integrated luminosity in pb^{-1}. Combining all errors in quadrature leads to the following estimates of the total error for $\mathcal{L} = 100(250,\ 500,\ 1000)pb^{-1}$ of $(+24.6, -18.3),\ (19.7, -14.0),\ (17.8, -12.3),\ (16.7, -11.4)$, respectively. At 95%CL, these errors yield the following allowed ranges for κ for the above integrated luminosities: $-0.14 \leq \kappa \leq 0.15$, $-0.11 \leq \kappa \leq 0.12$, $-0.09 \leq \kappa \leq 0.11$, and $-0.08 \leq \kappa \leq 0.11$, respectively. These results should be considered indicative of what may eventually be possible at the Tevatron.

Apart from the total $t\bar{t}$ production cross section, various distributions involving the top may show some sensitivity to finite κ. In Fig. 4. we show the p_t, rapidity(y), and $t\bar{t}$ invariant mass(M) distributions for different values of κ. As a first approximation, we see that the dominant effect of finite κ, especially in the case where κ is positive, is to apply an approximate rescaling of the SM result by the ratio of total cross sections. Although this might appear at first surprising, it is merely a reflection of the fact that most of the $t\bar{t}$ cross section arises from $\hat{s}$ values not far above threshold. Of course, at the highest values of p_t or M, one begins to see small deviations from this simple qualitative picture, especially for values of κ far from zero, but the cross sections in those parameter space regions are always very small. For example, the ratio of the p_t distribution for $\kappa = 1$ and the SM case is approximately flat for p_t's less than about 300 GeV. However, as the p_t is further increased, this ratio rises significant, *i.e.*, there is a high p_t tail induced by finite κ. Of course the cross sections for p_t's > 300 GeV are quite small and the $\kappa = 1$ case is an extreme example. For κ's in the $0 - 0.5$ range, there is very little sensitivity to increased κ values in the distributions apart from the overall rescaling factor.

As emphasized above, the dominant effect of non-zero κ in the threshold region is a simply an approximate rescaling of the SM cross section. Of course, near particular values of κ this approximation breaks down; a special example of this situation for the $q\bar{q} \rightarrow t\bar{t}$ subprocess, $\kappa = -1$, can be seen immediately from Eq. (2). For all $\kappa \neq -1$, the expression in the square brackets in Eq. (2) is finite whereas it vanishes for that particular value. Amongst other things, this would imply that the $t\bar{t}$ center of mass scattering angle(z) distribution should be quite different when $\kappa = -1$ from all other cases. This expectation is borne out by the results shown in Fig. 5, which shows the $z = cos\theta^*$ distribution after integration over M and y, summing both the $q\bar{q}$ and gg contributions. Here we see that in all cases the angular dependence is quite mild, owing to threshold dominance, except for the case $\kappa = -1$. From Figs. 4 and 5 it is clear that additional information on κ will be difficult to obtain from distribution measurements so that we simply have to rely on total cross section results to constrain κ.

In order to further motivate our analysis we briefly discuss a class of technicolor models[9, 10] with non-zero κ. Consider the gauge group $G = SU(N)_{TC} \times SU(3)_C \times SU(2)_L \times U(1)_Y$, together with the following technicolored fields: a right-handed $SU(2)_L$ doublet of technileptons $T_R(N, 1, 2, 0) = (U_R, D_R)^T$, two left-handed $SU(2)_L$ singlet technileptons $U_L(N, 1, 1, 1/2)$, $D_L(N, 1, 1, -1/2)$, all with charges $\pm\frac{1}{2}$, and a charge $\frac{1}{6}$ color triplet techniscalar $\omega(\overline{N}, 3, 1, 1/6)$. Transformation properties with respect to the technicolor group, $SU(N)_{TC}$, and the standard model gauge group have been included in parenthesis. For the purposes of our discussion we can ignore the first two quark families. Yukawa couplings to the third family are given by

$$\mathcal{L}_Y = \lambda_Q \omega \overline{Q_L} T_R + \overline{\lambda_t} \omega^* \overline{U_L} t_R + \overline{\lambda_b} \omega^* \overline{D_L} b_R + H.c., \tag{8}$$

where Q_L is the left-handed $SU(2)_L$ doublet of quarks, and t_R, b_R are the right-handed $SU(2)_L$ singlet quarks. ω acquires a mass from the scalar sector of the Lagrangian and a 'constituent' mass from technicolor dynamics.†

Technifermion condensates will induce top and bottom quark masses via techniscalar exchange‡ , in analogy with fermion mass generation via gauge boson exchange in extended

†Scalar technicolor models can be supersymmetrized in order to protect the masses of the scalars. In turn, supersymmetric flavour-changing neutral currents can be suppressed since a multi-TeV supersymmetry breaking scale is natural in this framework[11].

‡Additional quark masses can be generated by adding more techniscalars, more technileptons, or Higgs

technicolor models. In the limit $m_\omega >> \Lambda_{TC}$, where $\Lambda_{TC} \sim 1$ TeV, ω can be integrated out and one obtains

$$m_t \approx \lambda_Q \overline{\lambda_t} \frac{\langle \overline{U} U \rangle}{4 m_\omega^2}, \qquad m_b \approx \lambda_Q \overline{\lambda_b} \frac{\langle \overline{D} D \rangle}{4 m_\omega^2}. \tag{9}$$

The magnitude of the condensates is estimated to be[17]

$$\langle \overline{D} D \rangle = \langle \overline{U} U \rangle \approx \left(\frac{3}{N_{TC}} \right)^{\frac{1}{2}} 4\pi \left(\frac{v}{\sqrt{N_D}} \right)^3 \ \mathrm{GeV}^3, \tag{10}$$

where $v = 246$ GeV, and N_D (equal to one above) is the number of technifermion doublets, T_R. Chromomagnetic dipole moments are due to emmision of a gluon by the exchanged techniscalar. One obtains

$$\frac{\kappa}{2 m_t} \approx \frac{m_t(m_\omega)}{m_\omega^2} \tag{11}$$

at m_ω. Leading-order QCD evolution from TeV scales to $\mu \sim 2 m_t$ will reduce κ by a few percent and can be neglected for our purposes.

For κ to have a substantial effect on the $t\bar{t}$ production cross section m_ω must be small. Unfortunately, for $m_\omega \sim \Lambda_{TC}$ we can no longer simply integrate ω out to obtain expressions for m_t and κ since strong technicolor dynamics become important.[§] Nevertheless, we expect the above expressions to give the correct orders of magnitude and we defer a more sophisticated treatment to future investigation. Guided by estimates of the technifermion constituent mass[18], obtained by scaling of the QCD constituent mass (one obtains $m_{TC} \sim$ (300 MeV)$\frac{v}{\sqrt{N_D} f_\pi}$ or 800 GeV for $N_D = 1$, 550 GeV for $N_D = 2$), we assume that $m_\omega \gtrsim \frac{1}{2}$ TeV is a reasonable range to take in eqs. (9) and (11).[¶] So for $m_t \approx 170\ GeV$ we expect

doublets which acquire small vacuum expectation values by coupling to the technilepton condensates. Radiative mass contributions could, in principle, also play a role for light quark masses.

[§]For example, it may be that the exchanged techniscalar and technifermion bind so that the quark's mass can be attributed to mixing with composite heavy quarks.

[¶]Quark-techniscalar Yukawa couplings can vary substantially so that all quark masses can be generated

$\kappa \lesssim \frac{1}{4}$. Assuming a form factor of the form given in eq. (4), with Λ identified with m_ω, Figs. 2 and 3 imply that $\mathcal{O}(50\%)$ increases in the Tevatron $t\bar{t}$ production cross section may be possible.

In this paper, we have considered the influence of a non-zero chromomagnetic moment for the top quark, κ, on the production of $t\bar{t}$ pairs at the Tevatron for top masses near 170 GeV. Non-zero values of κ may be present in both compositeness and technicolor scenarios. In particular, our results can be summarized as follows:

(*i*) We have obtained born-level expressions for $q\bar{q}, gg \to t\bar{t}$ for arbitrary values of κ and used the SM NLO and gluon resummation 'K-factors' from[7] to obtain total cross sections and various distributions for top pair production at the Tevatron.

(*ii*) We explored the possible influence of including form factors with a finite scale parameter, Λ, instead of a simple constant value for κ. We found, since the cross section was dominated by $t\bar{t}$ invariant masses not far from threshold, that values of Λ in the 1-2 TeV or above were essentially indistinguishable from $\Lambda = \infty$. However, for smaller values of Λ, the κ dependence was found to be softened.

(*iii*) For top masses in the $m_t = 170$ GeV range, we demonstrated that the top pair production cross section was quite sensitive to the value of κ. Values of κ in the range $1/4 - 1/3$ were shown to increase the SM cross section to the level reported by CDF while still remaining consistent with the bounds from D0. Since κ is $\mathcal{O}(\frac{m_t^2}{\Lambda^2})$ if associated with top mass generation, such large values would likely be due to new physics at a scale Λ below a TeV. If the cross section was eventually found to agree with the SM expectations, we estimated the bounds on κ obtainable at the Tevatron as the integrated luminosity increases. Included in this analysis are uncertainties due to scale ambiguities, structure function variations,

with $\mathcal{O}(\frac{1}{2})$ TeV techniscalars. Furthermore, such light techniscalar masses do not pose a danger for flavor-changing neutral currents since the latter first arise at the one-loop level.

luminosity uncertainties, and estimates of NNLO contributions, as well as statistics. We found that from the total cross section alone the Tevatron will be able to probe values of $|\kappa| < 0.10 - 0.15$ in the not too distant future, potentially providing us with a new window to physics in the TeV region.

(iv) We explored the possibility that p_t, rapidity(y), top pair mass(M), and center of mass scattering angle$(cos\theta^*)$ distributions may provide additional constraints on a potential non-zero value for κ. This analysis found that once these distributions were rescaled by the ratio of the κ-dependent to SM cross section almost all of the sensitivity was found to lie in parameter regions where differential cross sections were very small. Our conclusion is that these various distributions are probably not too useful in obtaining additional constraints on κ beyond those obtainable from the total cross section.

(v) We discussed a class of scalar technicolor models in which both the top's mass and $\kappa \sim \frac{1}{4}$ could be due to exchange of a techniscalar with $\frac{1}{2}$ TeV mass. It is interesting that with the techniscalar's mass at $\frac{1}{2}$ TeV (flavor-changing) chromomagnetic dipole moments can also lead to suppression of the B semileptonic branching ratio and substantial $\Delta \mathrm{I} = \frac{1}{2}$ enhancement in K decays[10].

If an anomalous chromomagnetic moment for the top quark exists it will open a new window to new physics beyond the Standard Model.

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Figure Captions

Figure 1. Theoretical NLO cross section(dash-dotted curve) for $t\bar{t}$ production at the Tevatron, including gluon resummation, as a function of the top quark mass from the work of Laenen *et al.*[7] and the corresponding anticipated uncertainty due to scale choice(dotted curves). The data point is the CDF result, while the horizontal dashed line is the 95% CL upper limit reported by the D0 Collaboration.

Figure 2. LO calculation of $q\bar{q} \to t\bar{t}$ production cross section using CTEQ structure functions assuming $m_t = 170$ GeV as a function of κ. The dotted(dashed, dash-dotted, solid, square-dotted) curves correspond to $\Lambda = 0.25(0.5,\ 1,\ 2,\ \infty)$ TeV, respectively.

Figure 3. NLO cross sections for the $q\bar{q} \to t\bar{t}$(dash-dotted) and $gg \to t\bar{t}$(dotted) subprocesses as well as the total cross section(solid) at the Tevatron as functions of κ for $m_t = 170$ GeV using the CTEQ parton distribution functions. The horizontal dashed lines provide the $\pm 1\sigma$ CDF cross section determination while the horizontal dotted line is the D0 95% CL upper limit.

Figure 4. (a) p_t distribution for top quark pairs produced at the Tevatron assuming $m_t = 170$ GeV and CTEQ PD. The solid curve is the SM prediction and the upper(lower) dash-dotted, dashed, and dotted curves correspond to $\kappa = 1,\ 0.5,\ 0.25(-1,\ -0.5,\ -0.25)$, respectively. (b) Top pair invariant mass distributions for the same cases as shown in (a). (c) Top quark rapidity distributions for the same cases as shown in (a).

Figure 5. $cos\theta^*$ distribution for top-pair production as in Figure 4, except that the upper(lower) dash-dotted, dashed, and dotted curves correspond to $\kappa = 0.25,\ 0.5,\ 1(-0.25,\ -0.5,\ -1)$, respectively.