

Top Quark Production at the Tevatron: Probing Anomalous Chromomagnetic Moments and
Theories of Low Scale Gravity

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Abstract

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TOP QUARK PRODUCTION AT THE TEVATRON: PROBING ANOMALOUS CHROMOMAGNETIC MOMENTS AND THEORIES OF LOW SCALE GRAVITY

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We review the effects of an anomalous chromomagnetic moment on top quark pair production at the Tevatron for Run II. Apart from an overall rescaling by the total cross section these couplings have little influence on top production characteristics. We then examine how the exchange of a Kaluza-Klein tower of gravitons arising from the low scale quantum gravity scenario of Arkani-Hamed, Dimopoulos and Dvali influences top pair cross sections and several associated kinematical distributions. The data that will be available with Run II luminosities is shown to be sensitive to values of the effective Planck scale of order 1 TeV or more.

1 Introduction

The production of top quarks at the Tevatron and other high energy colliders may be sensitive to new physics beyond the electroweak scale. This new physics can take many forms but in a very large class of models it can be parameterized by a set of non-renormalizable operators. In this paper we consider how the existence of two of these operators, one of dimension-six while the other is dimension-eight, modifies the production properties of the top at the Tevatron. The first operator induces an anomalous chromomagnetic dipole moment coupling between the top and gluons and has already been studied in some detail. The second operator, which has yet to be examined, occurs in a new theory of low energy quantum gravity¹ and has nothing to do with the strong interactions but arises from the exchange of a Kaluza-Klein tower of gravitons. While the underlying physics behind these operators is completely different their influence on top production can be analyzed in a similar fashion. However, the two scenarios lead to remarkably different predictions which can be tested at Run II.

2 Dimension-Six Operators and Chromomagnetic Moments

Let us first consider the set of dimension-six operators that can lead to a modification of the coupling of a gluon to $t\bar{t}$. Demanding P , C , and CP conservation, one can show² that there are only two Standard Model(SM), *i.e.*, $SU(3)_c \times SU(2)_L \times U(1)_Y$, gauge invariant operators of dimension-six which can be constructed out of SM fields which lead to new physics at the corresponding $t\bar{t}g$ vertex. (It will be assumed that the lighter quarks do not experience these new interactions.) These two operators can be written as

$$\begin{aligned} \mathcal{L}_{int} = & \frac{c_1}{\Lambda^2} [\bar{q}_L \gamma^\mu T^a D^\nu q_L + \bar{t}_R \gamma^\mu T^a D^\nu t_R + h.c.] G_{\mu\nu}^a \\ & + \frac{c_2}{\Lambda^2} [\bar{q}_L \sigma^{\mu\nu} T^a \tilde{\phi} + h.c.] G_{\mu\nu}^a, \end{aligned} \quad (1)$$

where Λ is the scale of the new physics, the c_i are unknown coefficients of order unity, q_L is the left-handed doublet containing the top and bottom quarks, T^a are the usual $SU(3)_c$ generators, D^ν is the SM covariant derivative, $G_{\mu\nu}^a$ is the gluon field strength tensor, and $\tilde{\phi} = i\tau_2 \phi^*$ is the conjugate of the SM Higgs field. (If one gives up parity conservation or charge conjugation invariance only one additional new operator is introduced, whereas, if we surrender all of P , C and CP four additional operators arise².) Once the Higgs field obtains a vev, $v/\sqrt{2}$, and we place the top quark pair on shell the resulting effective $t\bar{t}g$ vertex, including the usual piece from QCD, can be written very simply as

$$\mathcal{L}_{eff} = g_s \bar{t} T_a \left(F_v \gamma_\mu G_a^\mu - \frac{\kappa}{4m_t} \sigma_{\mu\nu} G_a^{\mu\nu} \right) t, \quad (2)$$

where g_s is the usual $SU(3)_c$ coupling, G_a^μ is the gluon field and we make the identifications $\kappa = 2\sqrt{2}m_t v c_2 / \Lambda^2$ and $F_v = 1 - c_1 q^2 / \Lambda^2$ with q^2 being the invariant mass of the $t\bar{t}$ pair. The parameter κ can be identified as the anomalous chromomagnetic moment of the top quark; we observe that when $\kappa \neq 0$ a direct $ggt\bar{t}$ four-point function is induced as a result of gauge invariance. Note that for $\Lambda=1$ TeV and c_2 of order unity values of κ of order 0.1 are possible³.

The effects of $F_v \neq 1$ on top quark pair production via $q\bar{q} \rightarrow t\bar{t}$ are relatively straightforward to analyze² since they simply scale the strength of the ordinary QCD coupling by an additional q^2 -dependent amount. F_v is thus seen to act like a simple form factor. The effects associated with κ were examined much earlier⁴ as the existence of $\kappa \neq 0$ was originally motivated by problems in flavor physics⁵ as well as early high top cross section measurements. As one might guess, and as was explicitly demonstrated⁴ by Hikasa *et al.*, the effects of these two operators will be easily distinguishable at the Tevatron.

In order to examine the effects due to $\kappa \neq 0$, we must calculate the parton-level $q\bar{q} \rightarrow t\bar{t}$ (which dominates at Tevatron energies) and $gg \rightarrow t\bar{t}$ differential cross sections.

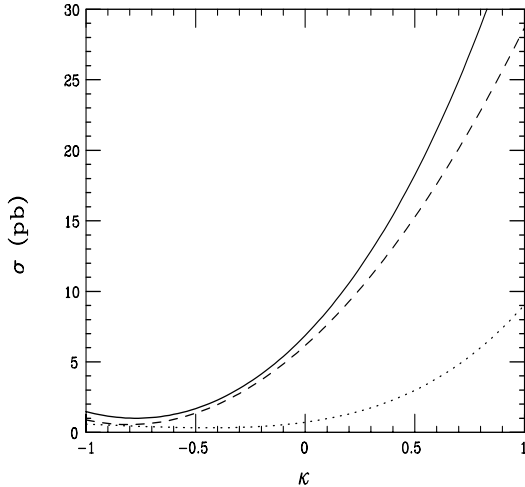


Figure 1: Cross section for $t\bar{t}$ production (solid) at Tevatron for Run II as a function of κ . The part of the cross section arising from $gg(q\bar{q})$ annihilation is shown by the dotted(dashed) curve.

For the $q\bar{q}$ case one obtains⁶

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

with \hat{s} being the parton level center of mass energy, $\beta^2 = 1 - 4m_t^2/\hat{s}$, and z being the cosine of the corresponding scattering angle, θ^* . m_t will be taken to be 175 GeV in the numerical discussion below. The corresponding cross section for $gg \rightarrow t\bar{t}$ is somewhat lengthy⁴ and not very enlightening except for the fact that it is quartic in κ . Both of these cross section expressions have also been generalized⁴ to allow for a CP -violating anomalous chromoelectric moment, $\tilde{\kappa}$ which can appear in cross section expressions in even powers only since cross sections are not CP -violating observables. Such a coupling arises from the CP -violating analogue of the operator proportional to c_2 in Eq.1 when the gluon field strength is replaced by its dual.

Several comments about the above cross section expression, which also apply to the gg initiated case, are now relevant. First, we see that $\kappa \neq 0$ modifies both the total cross section as well as the angular distribution. Second, the influence of κ grows rapidly with increasing \hat{s}/m_t^2 which implies that the effects for a fixed value of κ are more likely to be observed as the collider center of mass energy increases. Thus we may expect that κ is more easily probed at the LHC than it is at the Tevatron. Third, the differential cross section is sensitive to the *sign* of κ through the interference with the SM cou-

pling and this can lead to both a significant suppression or enhancement in the production rate.

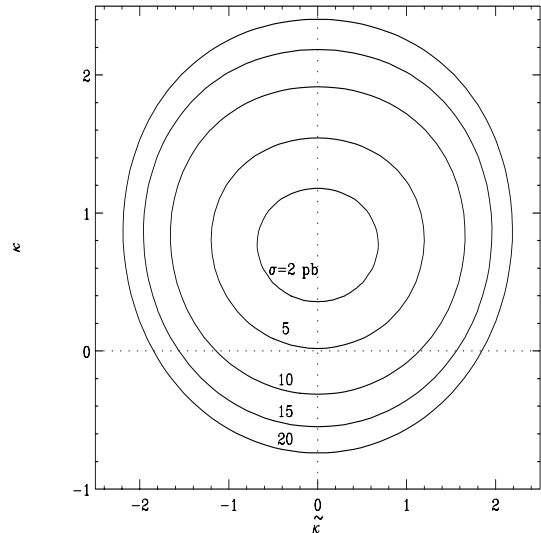


Figure 2: Same as Fig. 1 but now as a function of both κ and $\tilde{\kappa}$ from the work of Cheung in Ref. 4. The sign of κ is here opposite to that in Fig. 1.

To calculate the cross sections and associated distributions we employ the tree-level expression above, and the corresponding one for $gg \rightarrow t\bar{t}$, which are then corrected by K-factors⁴ in order to include the effects of higher order QCD corrections. For definiteness we use the CTEQ4M parton distribution functions⁷ although our numerical results will not be sensitive to this particular choice. The results of this cross section calculation for the Tevatron with $\sqrt{s} = 2$ TeV is shown in Fig.1. We see immediately that if κ is $\neq 0$ and of appreciable magnitude the top cross section can be significantly higher or lower than in the SM depending upon the sign of κ . This result can be used to constrain the value of κ provided no deviation from the SM prediction is observed. For example, assuming the SM cross section prediction was obtained experimentally and that the combined theoretical and experimental uncertainty on this measurement was at the level of 20%, we would deduce the bound $-0.10 \leq \kappa \leq 0.12$, which is beginning to probe an interesting range. Unfortunately, as we will soon see, it will be difficult for the Tevatron to do much better than this.

We note that if $\tilde{\kappa}$ were also non-zero, the two parameters would be difficult to disentangle using measurements that do not probe for CP -violation since $\tilde{\kappa}$ also modifies the production cross section. Fig.2 from the analysis of K. Cheung⁴ shows how the total cross section simultaneously varies with both of these parameters. Note that the presence of $\tilde{\kappa}$ can only lead to an increase in the cross section relative to the SM prediction and that the cross section is symmetric under $\tilde{\kappa} \rightarrow -\tilde{\kappa}$; this results from

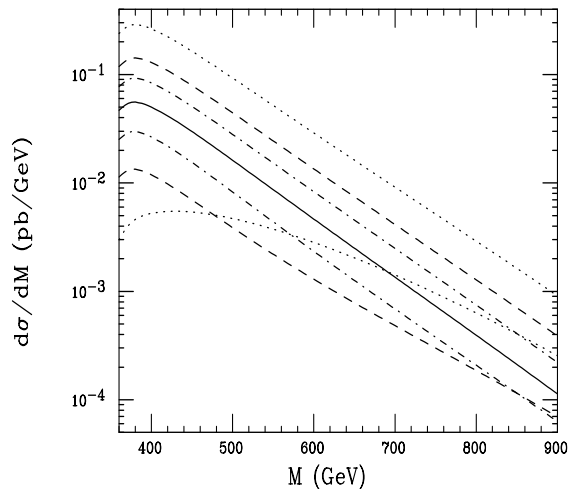


Figure 3: Top pair invariant mass distribution for top quark pairs produced at the Tevatron. The solid curve is the SM prediction and the upper(lower) dotted, dashed, and dash-dotted curves correspond to $\kappa = 1, 0.5, 0.25(-1, -0.5, -0.25)$, respectively.

the fact that this parameter appears only in even powers in the various cross section expressions since its contribution cannot interfere with the pure SM piece due to CP .

In an attempt to further probe $\kappa \neq 0$ we must explore the various kinematical distributions associated with top production. To this end we examine the top pair invariant mass distribution as well as the top quark p_t distribution which are shown in Figs.3 and 4, respectively. When initially examining either of these figures one may at first believe that both of these distributions show a substantial sensitivity to $\kappa \neq 0$. However, a longer second look reveals that the sets of curves are mostly parallel especially if the magnitude of κ is not too large.

To see what this means let us form the cross section ratios R_M and R_{p_t} by dividing out the κ -dependent predictions by those of the SM; the results of this exercise are displayed in Figs.5 and 6. These figures show, for values of κ in the range $|\kappa| \leq 0.25$ (and even for a somewhat larger interval), that the ratio of cross sections is at most slowly varying and is essentially constant, *i.e.*, is independent of M and/or p_t . Numerically, one finds that this constant ratio is just the ratio of the *total cross sections* observed in Fig.1. Thus we see that for relatively small, but phenomenologically interesting, values of κ we learn no new information in this case from the p_t or M distributions except to verify the result of the total cross section measurements.

What about other kinematic variables? Figs.7 and 8 display the top rapidity and angular distributions for the same set of κ values as considered above. Unfortunately,

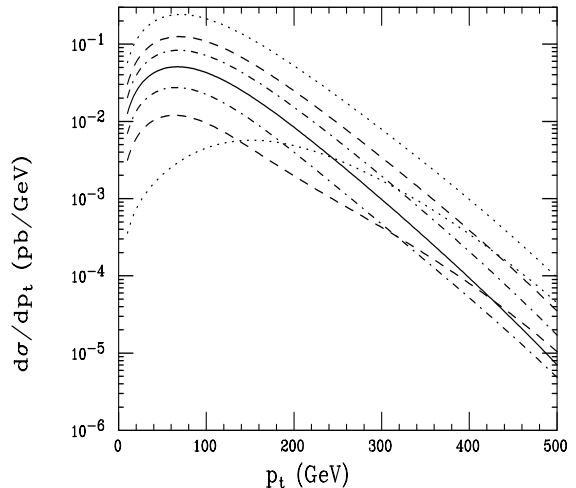


Figure 4: p_t distributions of the top quark for the same κ cases as shown in the previous figure.

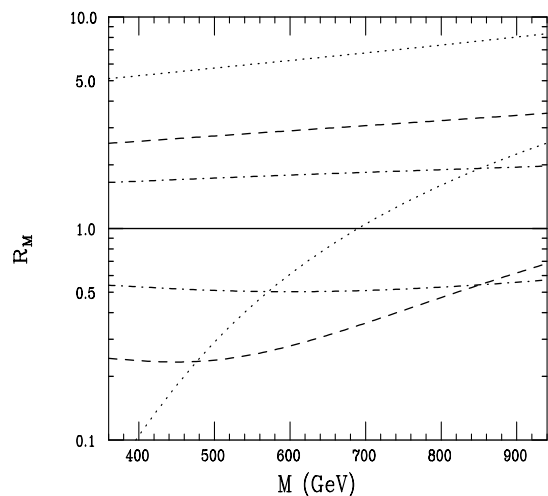


Figure 5: Ratios of the top pair invariant mass distributions for the various κ values shown in Fig.3 to those of the SM.

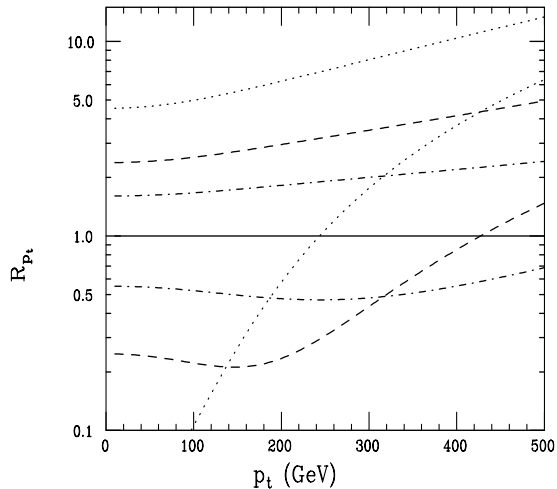


Figure 6: Ratios of the top quark p_t distributions for the various κ values shown in Fig.4 to those of the SM.

it is again fairly obvious that for the relevant range of κ the shapes of both of these distributions provide us with little or no extra sensitivity to κ and again merely confirm the results from the total cross section.

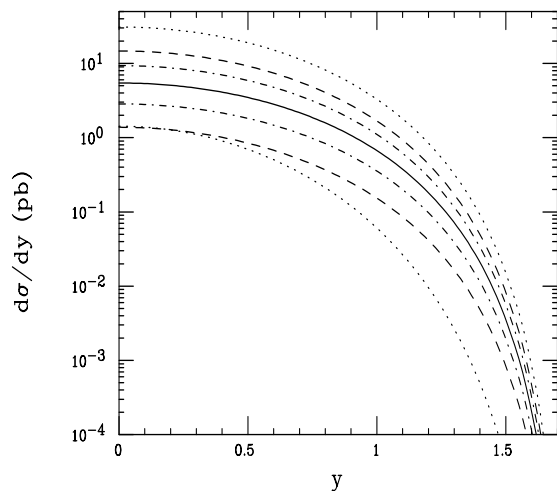


Figure 7: Top quark pair rapidity distributions for the same cases as shown in Fig.3.

The above analysis shows that conventional top quark kinematical distributions are no more sensitive to κ than is the total cross section itself. To try to bridge this problem, Cheung⁴ examined the rate for single jet production, with fixed minimum p_t , in association with a top quark pair. This required the complete calculation

of the $q\bar{q}$, $gg \rightarrow t\bar{t}g$ and $qg \rightarrow t\bar{t}q$ subprocesses including the full κ dependence. Cheung then compared the event rates for final states containing an additional jet with a fixed minimum p_t as the value of κ (and $\tilde{\kappa}$) was allowed to vary. For a minimum $p_t > 20 - 25$ GeV the sensitivity of this reaction was found to be comparable to that obtained from the total cross section, although with completely different systematic errors. For lower minimum values of p_t the sensitivity was reduced, whereas for higher minimum values of p_t there is a loss in statistical power. It thus remains true that the Tevatron's sensitivity to κ is essentially given by the bounds from the total cross section.

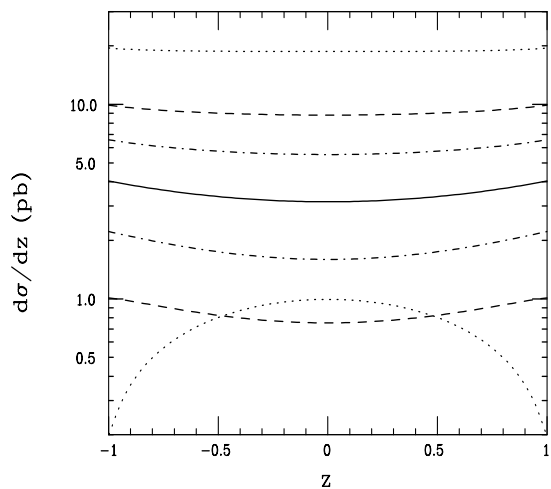


Figure 8: $z = \cos\theta^*$ distribution for top-pair production as in Figure 3, except that the upper(lower) dash-dotted, dashed, and dotted curves correspond to $\kappa = 0.25, 0.5, 1(-0.25, -0.5, -1)$, respectively.

Before concluding this section we would like to briefly mention how the determination of κ differs at the LHC where there is no shortage of statistics in top pair production. In this case it has been shown that the total cross section is somewhat less sensitive to κ than at the Tevatron but the long lever arms in M and, in particular, p_t lead to substantially increased sensitivity. A preliminary study done during Snowmass '96⁴ found that the LHC, through performing fits to these two distributions, was sensitive to values of $|\kappa|$ as small as 0.04, which is about a factor of three better than the Tevatron.

3 Low Scale Quantum Gravity

Arkani-Hamed, Dimopoulos and Dvali(ADD)¹ have recently proposed a radical solution to the hierarchy problem. ADD hypothesize the existence of n additional large

spatial dimensions in which gravity can live, called ‘the bulk’, whereas all of the fields of the Standard Model are constrained to lie on ‘a wall’, which is our conventional 4-dimensional world. Gravity only appears to be weak in our ordinary 4-dimensional space-time since we merely observe it’s action on the wall. It has recently been shown¹ that a scenario of this type may emerge in string models where the effective Planck scale in the bulk is identified with the string scale. In such a theory the hierarchy can be removed by postulating that the string or effective Planck scale in the bulk, M_s , is not far above the weak scale, *e.g.*, a few TeV. Gauss’ Law then provides a link between the values of M_s , the conventional Planck scale M_{pl} , and the size of the compactified extra dimensions, R ,

$$M_{pl}^2 \sim R^n M_s^{n+2}, \quad (4)$$

where the constant of proportionality depends not only on the value of n but upon the geometry of the compactified dimensions. Interestingly, if M_s is near a TeV then $R \sim 10^{30/n-19}$ meters; for separations between two masses less than R the gravitational force law becomes $1/r^{2+n}$. For $n = 1$, $R \sim 10^{11}$ meters and is thus obviously excluded, but, for $n = 2$ one obtains $R \sim 1$ mm, which is at the edge of the sensitivity for existing experiments. For $2 < n \leq 7$, where 7 is the maximum value of n being suggested by M-theory, the value of R is further reduced and thus we may conclude that the range $2 \leq n \leq 7$ is of phenomenological interest.

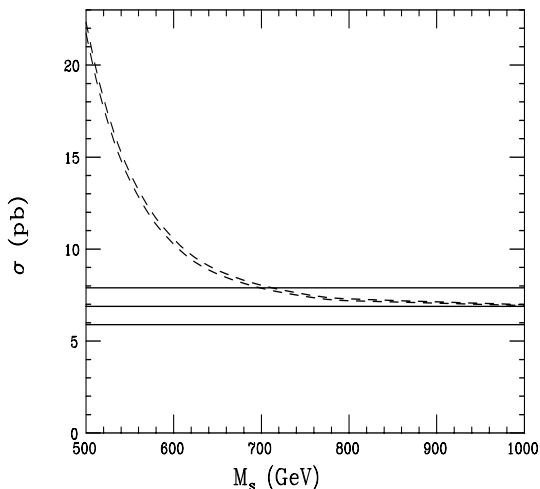


Figure 9: Top pair production cross section at Run II of the Tevatron as a function of the string scale M_s . The solid band represents an approximate 15% error on the cross section determination. Although the results for both $\lambda = \pm 1$ are shown they are visually difficult to separate.

The phenomenology of the ADD model has now be-

gun to be addressed in a series of recent papers⁸. The Feynman rules can be obtained by considering a linearized theory of gravity in the bulk, decomposing it into the more familiar 4-dimensional states and recalling the existence of Kaluza-Klein towers for each of the conventionally massless fields. The entire set of fields in the K-K tower couples in an identical fashion to the particles of the SM. By considering the forms of the $4 + n$ symmetric conserved stress-energy tensor for the various SM fields and by remembering that such fields live only on the wall one may derive all of the necessary couplings. An important result of these considerations is that only the massive spin-2 K-K towers (which couple to the 4-dimensional stress-energy tensor, $T^{\mu\nu}$) and spin-0 K-K towers (which couple proportional to the trace of $T^{\mu\nu}$) are of phenomenological relevance as all the spin-1 fields can be shown to decouple from the particles of the SM. For processes that involve massless fermions at one vertex and massless gauge fields, as will be the case below, the contributions of the spin-0 fields can also be ignored.

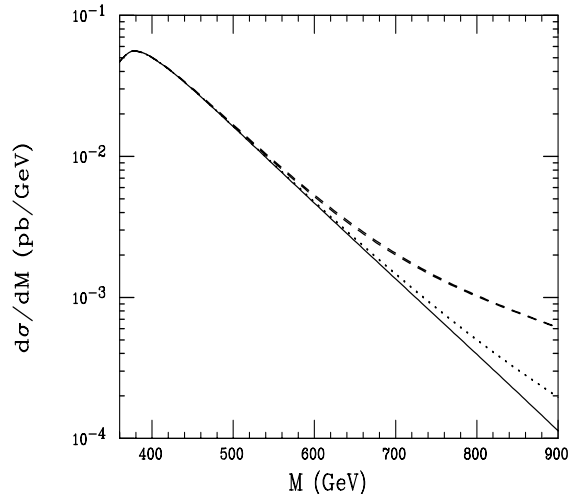


Figure 10: Top pair invariant mass distribution at Run II of the Tevatron assuming the SM (solid) or $M_s = 800(1000)$ GeV as the dashed(dotted) curve.

Given the Feynman rules as developed in⁸ it appears that the ADD scenario has two basic classes of collider tests. In the first class, a K-K tower of gravitons can be emitted during a decay or scattering process leading to a final state with missing energy. The rate for such processes is strongly dependent on the number of extra dimensions. In the second class, which we consider here, the exchange of a K-K graviton tower between SM fields can lead to almost n -independent modifications to conventional cross sections and distributions or can possibly lead to new interactions. The exchange of the graviton

K-K tower leads to an effective color-singlet contact interaction operator of dimension-eight with a scale set by the parameter M_s for both the $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$ processes. The single overall order one coefficient, λ , is unknown but its value is conventionally set to ± 1 . Given these two operators the relevant cross sections and distributions can be calculated directly.

For the process $q\bar{q} \rightarrow t\bar{t}$, we obtain

$$\frac{d\sigma_{q\bar{q}}}{dt} = \frac{d\sigma_{q\bar{q}}^{SM}}{dt} + \frac{\pi(\lambda K \hat{s})^2}{64M_s^8} [1 - 3\beta^2 z^2 + 4\beta^4 z^4 - (1 - \beta^2)(1 - 4\beta^2 z^2)] , \quad (5)$$

where β , M_s and z have been defined above, which apart from a color factor was first obtained by Hewett⁸ and which agrees with the expression given by Mathews, Raychaudhuri and Sridhar⁸. For $K = 1(\frac{2}{\pi})$ we obtain the operator normalization employed by Giudice, Rattazzi and Wells(Hewett)⁸; for numerical analyses we will assume $K = \frac{2}{\pi}$ to make comparisons with other results obtained previously. Note that there is no interference between the SM contribution, which is pure color octet due to single gluon exchange, and that from the color-singlet graviton tower exchange; hence the sign of λ is irrelevant in this case. Note that this term can only lead to an increase in the top production cross section.

Similarly, for $gg \rightarrow t\bar{t}$, we find

$$\begin{aligned} \frac{d\sigma_{gg}}{dt} = & \frac{d\sigma_{gg}^{SM}}{dt} - \frac{3\pi}{64\hat{s}^2} \left[\frac{4(\lambda K)^2}{M_s^8} \right. \\ & \left. - \frac{8\alpha_s \lambda K}{3M_s^4(m_t^2 - \hat{t})(m_t^2 - \hat{u})} \right] [6m_t^8 - 4m_t^6(\hat{t} + \hat{u}) \\ & + 4m_t^2 \hat{t}\hat{u}(\hat{t} + \hat{u}) - \hat{t}\hat{u}(\hat{t}^2 + \hat{u}^2) + m_t^4(\hat{t}^2 + \hat{u}^2 \\ & - 6\hat{t}\hat{u})] , \quad (6) \end{aligned}$$

with $\hat{t}, \hat{u} = \frac{-1}{2}\hat{s}(1 \mp \beta z) + m_t^2$ and which agrees with the result obtained by Mathews, Raychaudhuri and Sridhar⁸. In this expression we see that an interference with the SM contribution does occur so that the sign of λ is now relevant. This interference originates from the t - and u -channel SM graphs which have color singlet components. Numerically, the sign of λ will remain relatively unimportant since the $gg \rightarrow t\bar{t}$ subprocess is suppressed at the Tevatron in comparison to $q\bar{q} \rightarrow t\bar{t}$.

In Fig.9 we show the top pair cross section for Run II as a function of M_s for $\lambda = \pm 1$; these two curves are hardly separable with the difference due entirely to the SM-graviton tower interference term in the $gg \rightarrow t\bar{t}$ subprocess. Here we see that for M_s less than about 700 GeV the cross section becomes substantially larger than the SM prediction. Assuming that the SM value for the cross section was obtained experimentally would imply a value of M_s greater than this value. This is

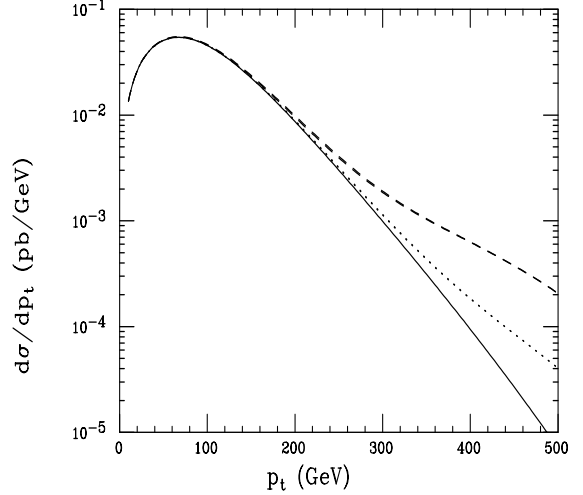


Figure 11: Same as the previous figure but now for the top p_t distribution.

consistent with the corresponding results of the Run I analysis by Mathews, Raychaudhuri and Sridhar⁸. To set the scale for this lower bound on M_s , we note that Hewett has shown⁸ that the Tevatron at Run II, through the Drell-Yan process, should be sensitive to M_s up to $\simeq 1.1$ TeV with a comparable sensitivity anticipated from LEP II. In addition, Rizzo⁸ has shown that HERA may also eventually reach a similar level of sensitivity of $\simeq 1.1$ TeV. Evidently, we must go beyond the total cross section measurement⁹ if we want to improve the M_s reach using top production.

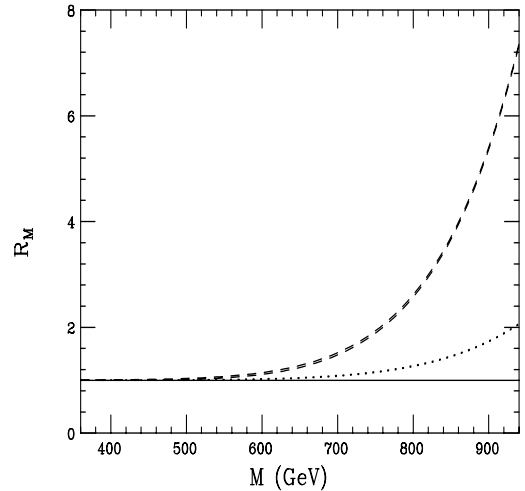


Figure 12: Ratios of the top pair invariant mass distributions for the two values of M_s shown in Fig.10 to those of the SM.

Figs.10 and 11 show the $t\bar{t}$ mass distribution and top quark p_t distribution, respectively, for the SM and when $M_s = 800$ or 1000 GeV. (The two sets of curves corresponding to $\lambda = \pm 1$ are shown but are not visually separable.) In the case of the top pair mass distribution no deviation from the SM is observed below invariant masses of $\simeq 600$ GeV where the three curves start to diverge. A similar situation is seen in the p_t distribution below 200 GeV. To clarify the situation, we again form the ratios of predictions R_M and R_{p_t} shown in Figs.12 and 13. Both these ratios take off once the M_s scale begins to be probed. (One may worry, based on unitarity arguments, that it is not valid to examine top pair invariant masses larger than the scale M_s . Guidice, Rattazzi and Wells⁸ have shown that unitarity remains satisfied for values of $M \leq 1.6M_s$, using our normalization convention, so that all our plots are cut off before this point is reached.)

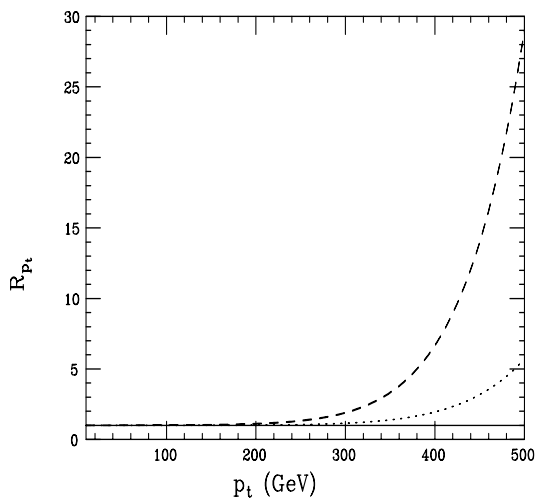


Figure 13: Ratios of the top quark p_t distributions for the two values of M_s shown in Fig.11 to those of the SM.

To get an idea of the sensitivity of these distributions we have performed a simple Monte Carlo study. Assuming that the data reproduces the SM expectation and that the data below a certain cutoff can itself be used to normalize the distribution, then a 95% CL lower bound on M_s can be obtained for a given fixed integrated luminosity. In the case of the mass distribution, we assume that the SM is applicable below $M = 500$ GeV, as is reasonable from the figures, and fit Monte Carlo generated data to the M_s -dependent distribution for values of M in excess of 600 GeV. Following this approach, for a integrated luminosity of $2(20) fb^{-1}$ we obtain a 95% CL lower limit on M_s of $1.05(1.22)$ TeV with the sign of λ de-

pendence being less than 1%. Similarly, we assume that the p_t distribution below 200 GeV is controlled by the SM and perform a M_s -dependent fit for $p_t > 300$ GeV. For the luminosities above we obtain the corresponding 95% CL lower bounds of $M_s > 1.02(1.18)$ TeV, which are comparable to the previous results. Both sets of constraints are seen to be very similar to what is obtainable from Drell-Yan, LEP II and HERA data.

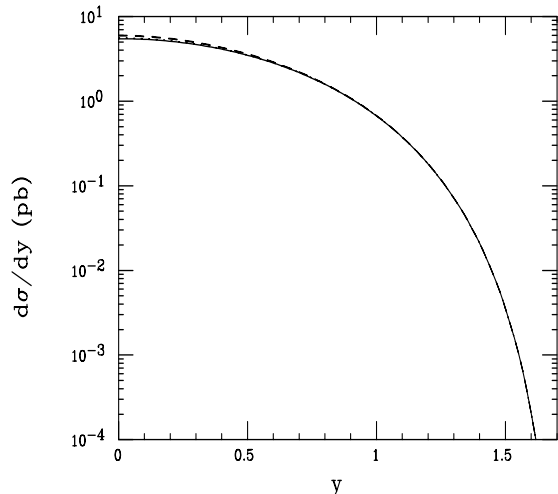


Figure 14: Top quark rapidity distribution at the Run II Tevatron for the SM(solid) and when the string scale M_s is set to 800(1000) GeV corresponding to the dashed(dotted) curve.

What about the rapidity and angular distributions? These are presented in Figs.14 and 15. As can be seen, the rapidity distribution tells us essentially nothing since it is almost independent of M_s for these values. Similarly, the angular distribution shown in Fig.15 displays only a very modest M_s dependence. We conclude that little additional information on M_s can be obtained from these distributions.

Before concluding this section we would again like to briefly mention the situation at the LHC⁹. As one might expect the overall sensitivity to M_s is here substantially increased and the sign of λ becomes more important. The total cross section itself is found to be less sensitive to M_s ; a 15% measurement can probe values of M_s only below $\simeq 1.8$ TeV. On the otherhand, fits to the p_t and M distributions similar to those discussed above yield *discovery* reaches as high as 5.7-6.3 TeV assuming an integrated luminosity of $100 fb^{-1}$. This reach is comparable to that obtainable using the Drell-Yan process as shown by Hewett⁸ and that which can be achieved at a 1 TeV e^+e^- linear collider.

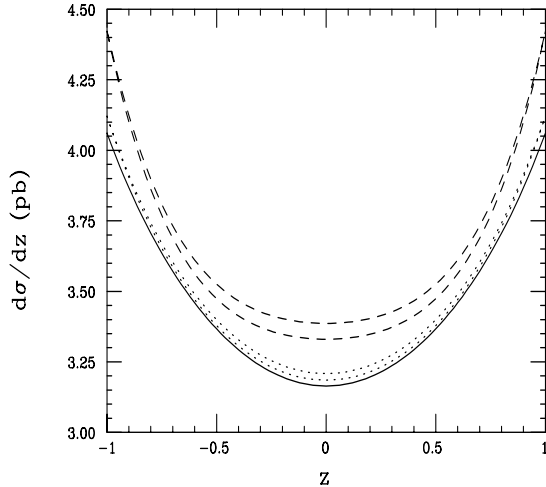


Figure 15: Top quark angular distribution at the Run II Tevatron for the SM(solid) and when the string scale M_s is set to 800(1000) GeV corresponding to the dashed(dotted) curves. Note that the two cases $\lambda = \pm 1$ are separable in this plot.

4 Summary and Conclusion

The production properties of top quark pairs at the Tevatron can be uniquely sensitive to new physics beyond the SM. Here we have explored two types of new physics that appear as non-renormalizable, higher dimensional operators.

In the first example, a dimension-six P and C conserving modification of the $t\bar{t}g$ vertex was shown to lead to an effective anomalous chromomagnetic moment for the top quark. At Tevatron energies this new interaction leads to essentially only one effect, *i.e.*, the modification of the top pair production cross section. In this case all distributions, to first approximation, were shown to simply scale up or down by the same amount. Assuming the SM prediction for the cross section is obtained at Run II with $2 fb^{-1}$ of integrated luminosity we obtain the approximate bound $-0.10 \leq \kappa \leq 0.12$.

In the case of low scale quantum gravity, the exchange of a Kaluza-Klein tower of gravitons leads to a pair of dimension-eight, color singlet operators that contribute to $t\bar{t}$ production with the effective Planck mass setting their scale. Unlike the case of the top quark anomalous chromomagnetic moment these operators induce distinctive modifications in both the total cross section as well as the top pair invariant mass and top transverse momentum distributions. By looking for deviations in these distributions at Run II we obtained sensitivities to the string scale of order 1 TeV. This can be increased by more than a factor of five in the case of the LHC.

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