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Testing TeV scale quantum gravity using dijet production at the Tevatron

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Abstract: Dijet production at the Tevatron including effects of virtual exchanges of spin-2 Kaluza-Klein modes in theories with large extra dimensions is considered. The experimental dijet mass and angular distribution are exploited to obtain stringent limits (> 1.2 TeV) on the effective string scale M_S.

Keywords: Beyond Standard Model, Compactification and String Models.

In recent years, there have been major breakthroughs in the understanding of string theories at strong coupling in the framework of what is now known as M-theory [1, 2, 3]. In particular, unification of gravity with other interactions now seems possible in the M-theoretic framework. But of tremendous interest to phenomenology is the possibility that the effects of gravity could become large at very low scales ($\sim$ TeV), because of the effects of large extra compact dimensions where gravity can propagate [4]. Starting from a higher-dimensional theory of open and closed strings [5, 6], the effective low-energy theory is obtained by compactifying to $3+1$ dimensions, in such a way that d of these extra dimensions are compactified to a common scale R which is large, while the remaining dimensions are compactified to extremely tiny scales which are of the order of the inverse Planck scale. In such a scenario, the Standard Model (SM) particles correspond to open strings, which end on a 3-brane and are, therefore, confined to the $(3+1)$-dimensional spacetime. On the other hand, the gravitons (corresponding to closed strings) propagate in the $(4+d)$-dimensional bulk. The relation between the scales in $(4+d)$ dimensions and in 4 dimensions is given by [4]

$$M_{\mathrm{P}}^2 \sim M_S^{d+2} R^d \,, \tag{1}$$

where M_S is the low-energy effective string scale. This equation has the interesting consequence that we can choose M_S to be of the order of a TeV and thus get around the hierarchy problem. For such a value of M_S, it follows that $R = 10^{32/d-19}\,\mathrm{m}$, and so we find that M_S can be arranged to be a TeV for any value $d > 1$. Effects of non-newtonian gravity can become apparent at these surprisingly low values of energy. For example, for $d = 2$ the compactified dimensions are of the order of 1 mm, just below the experimentally tested region for the validity of Newton's law of gravitation and within the possible reach of ongoing experiments [7]. In fact, it has been shown [8] that it is possible to construct a phenomenologically viable scenario with large extra dimensions, which can survive the existing astrophysical and cosmological constraints. This idea, proposed by Arkani-Hamed, Dimopoulos and Dvali [4, 5], may be referred to as the ADD model. For some early papers on large Kaluza-Klein dimensions, see refs. [11, 12] and for recent investigations on different aspects of the TeV scale quantum gravity scenario and related ideas, see ref. [13].

Below the scale M_S [14, 15, 16], we have an effective theory with an infinite tower of massive Kaluza-Klein states, which contain spin-2, spin-1 and spin-0 excitations. The spin-1 couplings to the SM particles in the low-energy effective theory decouple from matter, whereas the scalar modes couple to the trace of the energy-momentum tensor, which vanishes for massless particles. Other particles related to brane dynamics (for example, the Y modes which are related to the deformation of the brane) have effects which are subleading, compared to those of the graviton. The only states, then, that contribute to low-energy phenomenology with initial-state light particles are the spin-2 Kaluza-Klein states. For graviton momenta smaller than the scale M_S, the effective description reduces to one where the gravitons in the bulk propagate in the flat background and couple to the SM fields via a (four-dimensional) induced metric $g_{\mu\nu}$. The interactions of the SM particles with the graviton, $G_{\mu\nu}$, at the lowest order, can be derived from the following effective lagrangian:

$$\mathcal{L} = -\frac{1}{\bar{M}_P} \sum_n G^{(n)}_{\mu\nu} T^{\mu\nu} \, , \tag{2}$$

where n labels the Kaluza-Klein mode, $\bar{M}_P = M_P/\sqrt{8\pi}$ and $T^{\mu\nu}$ is the energy-momentum tensor. Given that the effective lagrangian given in eq. (2) is suppressed by $1/\bar{M}_P$, it may seem that the effects at colliders will be hopelessly suppressed. However, in the case of real graviton production, we have to sum over the whole tower of Kaluza-Klein states, as a result, the phase space for the Kaluza-Klein modes cancels the dependence on $\bar{M}_P$ and, instead, provides a suppression of the order of M_S^{-4}. For the case of virtual production, we again have to sum over the whole tower of Kaluza-Klein states and this sum when properly evaluated [16, 15] provides the correct order of suppression ($\sim M_S^{-4}$). The summation of time-like propagators and space-like propagators yield exactly the same form for the leading terms in the expansion of the sum [16] and this shows that the low-energy effective theories for the s- and t-channels are equivalent to the lowest order.

Recently, several papers have explored the consequences of the above effective lagrangian for experimental observables at high-energy colliders. In particular, direct searches for graviton production at e^+e^-, $p\bar{p}$ and pp colliders, leading to spectacular single photon + missing energy or monojet + missing energy signatures, have been suggested [15]–[18]. The virtual effects of graviton exchange in $e^+e^- \to f\bar{f}$ and in high-mass dilepton production [19], in $t\bar{t}$ production [20] at the Tevatron and the LHC, and in deep-inelastic scattering at HERA [21] have been studied. The bounds on M_S obtained from direct searches depend on the number of extra dimensions. Non observation of the Kaluza-Klein modes yield bounds which are around 500 GeV to 1.2 TeV at LEP2 [17, 18] and around 600 GeV to 750 GeV at Tevatron (for n between 2 and 6) [17]. Indirect bounds from virtual graviton exchange in dilepton production at Tevatron yields a bound of around 950 GeV [19]. Virtual effects in $t\bar{t}$ production at Tevatron yields a bound of about 650 GeV [20], while from deep-inelastic scattering a bound of 550 GeV results [21]. At LHC, it is expected that $t\bar{t}$ production can be used to explore a range of M_S values upto 4 TeV [20]. More recently, these studies have been extended to the case of e^+e^- and $\gamma\gamma$ collisions at the NLC [22, 23]. There have also been papers discussing the implications of the large dimensions for Higgs production [24] and electroweak precision observables [25]. Astrophysical constraints, like bounds from energy loss for supernovae cores, have also been discussed [26].

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In the present work, we study the effect of the virtual graviton exchange on the dijet production cross-section in $p\bar{p}$ collisions at the Tevatron. The presence of the new couplings from the low-energy effective theory of gravity leads to new diagrams for dijet production. For the sake of brevity, we do not present the diagrams here, but limit ourselves to a list of the sub-processes which contribute to this signal. These are

- $q\, q' \longrightarrow q\, q'$ (t channel) ,
- $q\, \bar{q}' \longrightarrow q\, \bar{q}'$ (t channel) ,
- $\bar{q}\, \bar{q} \longrightarrow \bar{q}\, \bar{q}$ (t and u channels) ,
- $q\, \bar{q} \longrightarrow q\, \bar{q}$ (s and t channels) ,
- $g\, g \longrightarrow q\, \bar{q}$ (s, t and u channels) ,
- $\bar{q}\, g \longrightarrow \bar{q}\, g$ (s, t and u channels) ,
- $\bar{q}\, \bar{q}' \longrightarrow \bar{q}\, \bar{q}'$ (t channel) ,
- $q\, q \longrightarrow q\, q$ (t and u channels) ,
- $q\, \bar{q} \longrightarrow q'\, \bar{q}'$ (s channel) ,
- $q\, \bar{q} \longrightarrow g\, g$ (s, t and u channels) ,
- $q\, g \longrightarrow q\, g$ (s, t and u channels) ,
- $g\, g \longrightarrow g\, g$ (s, t and u channels) ,

where q can be any of u, d or s as applicable and q' denotes another quark of different flavour. To each QCD diagram with a gluon exchange, there corresponds a similar diagram with a spin-2 Kaluza-Klein graviton exchange. Using the couplings given in refs. [15, 16], and summing over all the graviton modes, we have calculated the sub-process cross-section (including the all-important interference effects) due to the new physics.[1] This has then been incorporated into a parton-level Monte-Carlo event generator, which, while neglecting fragmentation effects, still yields reasonably good results when the angular separation of the parent partons is large, which is mostly the case in the present study.

For s-channel processes, the sum over all graviton modes involves a sum over propagators, of the form [16]

$$D(\hat{s}) = \frac{1}{\bar{M}_{\rm P}^2} \sum_n \frac{1}{\hat{s} - M_n^2} \simeq -i \frac{\lambda_s^{(d)}(\hat{s})}{M_S^4} \equiv i \frac{\pm 1}{\widetilde{M}_S^4} \tag{3}$$

absorbing the magnitude of the effective coupling $\lambda_s^{(d)}(\hat{s})$ into an effective string scale $\widetilde{M}_S^4$. Under the low-energy approximation $\hat{s} \ll M_S^2$, we can write

$$\begin{aligned} \lambda_{s0}^{(d)}(\hat{s}) &= \log\left(M_S^2/\hat{s}\right) \qquad \text{for } d = 2 \\ &= (d-2)^{-1} \qquad \text{for } d > 2 \,, \end{aligned} \tag{4}$$

which is either constant or varies very slowly with $\hat{s}$. We thus see that the graviton induced cross-sections involve just two new parameters: the effective string scale M_S and the sign of λ_s. This may be referred to as the constant-λ approximation. In

[1] The explicit expressions for the subprocess cross-sections will appear in a future publication [27].

mass bins		241-300	300-400	400-517	517-625	> 625	Combined
CDF	$\lambda = +1$	585	587	753	873	1095	1070
	$\lambda = -1$	626	544	717	852	1075	1108
mass bins		260-425	425-475	475-635	> 635		Combined
D0	$\lambda = +1$	523	632	919	1154		1160
	$\lambda = -1$	500	614	896	1131		1159

Table 1: 95% C.L. limits on $\widetilde{M}_S$ derived from the χ distribution. All masses are in GeV.

general, the sign of λ_s is not known á priori in effective theories. We keep the sign of λ_s as a parameter, therefore, in all our calculations using the constant-λ approximation. Similar considerations hold for t- and u-channel processes, with a somewhat different functional form $\lambda_t^{(d)}(\hat{t})$. However, in the low-energy approximation $|\hat{t}| \ll M_S^2$, the function $\lambda_{t0}^{(d)}(\hat{t})$ has, as mentioned above, the same functional form as the sum of s-channel propagators in eq. (4).

Significant changes in the angular distribution of jets are expected when spin-2 particle exchanges are added to the spin-1 exchange of the SM. With this in mind, we study the normalised χ distribution, $\frac{1}{N}\frac{dN}{d\chi}$, where the variable χ is defined as

$$\chi \equiv \exp|\eta_1 - \eta_2| \simeq \frac{\hat{u}}{\hat{t}}\,, \tag{5}$$

with η_1 and η_2 being the pseudo-rapidities of the two jets, so as to be able to compare with the experimental results from the CDF [28] and the D0 [29] collaborations. The approximate equality in eq. (5) is exact in a parton-level analysis. The χ distributions in both the experiments have been calculated in different mass bins, and we have used the same binning as used by the two experiments. Using the same kinematic cuts as used by the experimentalists (insofar as can be implemented in a parton-level analysis), we study the normalised χ distribution as a function of the effective string scale, $\widetilde{M}_S$, and obtain the 95% C.L. limits by doing a χ^2 fit to the data in each invariant mass bin as well as to the data integrated over the entire mass range. For our computations, we have used CTEQ4M parton densities [30] taken from PDFLIB [31]. Details of this analysis will be presented elsewhere [27]. However, the main conclusions are discussed below.

The 95% C.L. limits on $\widetilde{M}_S$ derived from the CDF and the D0 χ distributions, respectively, are displayed in table 1 for the cases $\lambda = \pm 1$. We find that the χ distribution integrated over the entire mass range yields a limit of 1070 (1108) GeV for $\lambda = 1(-1)$ for CDF and a limit of 1160 (1159) GeV for $\lambda = 1(-1)$ for D0. These bounds are the most stringent yet obtained from processes involving virtual graviton exchange. Interestingly, the bounds obtained by considering the highest mass bin are almost as good as those obtained by comparing with all the data.

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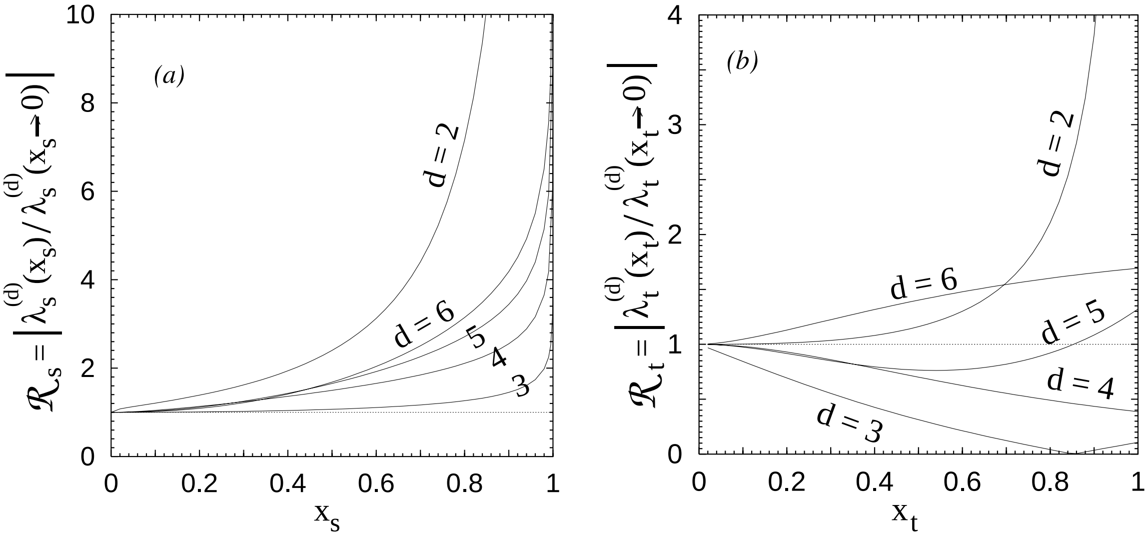

Figure 1: Illustrating the validity of the constant-λ approximation for (a) s-channel and (b) t-channel graviton exchange processes.

As explained above, the approximation in eq. (4) breaks down as $\hat{s} \to M_S$. In figure 1, we present curves for $d = 2, 3, 4, 5$ and 6, illustrating the behaviour of the ratios

$$(a)\ \mathcal{R}_s \equiv \left| \frac{\lambda_s^{(d)}(x_s)}{\lambda_{s0}^{(d)}(x_s)} \right|, \qquad (b)\ \mathcal{R}_t \equiv \left| \frac{\lambda_t^{(d)}(x_t)}{\lambda_{t0}^{(d)}(x_t)} \right| \tag{6}$$

with variation in the argument $x_s = \sqrt{\hat{s}}/M_S$ or $x_t = \sqrt{-\hat{t}}/M_S$, as the case may be. In the low-energy approximation, both ratios are unity by definition and the singular behaviour as the argument tends to unity is symptomatic of an effective theory. It is immediately obvious that $\mathcal{R}_s$ remains less than about 2 for a significant energy regime. A deviation as large as $\mathcal{R}_s = 2$, will, however, change the effective $\widetilde{M}_S$ only by a factor $2^{1/4} \simeq 1.2$. Almost all the data used to put a bound on $\widetilde{M}_S$ from the χ distribution belong to the energy regime where the low-energy approximation holds (it should be noted that both the CDF and D0 Collaborations have very few events with invariant mass above 700 GeV). We thus conclude that the bounds derived from the χ distributions using a constant-λ approximation are fairly robust, except possibly in the case $d = 2$. (In this case, however, astrophysical bounds are so strong as to make bounds from terrestrial experiments practically redundant.)

The fact that the bounds on $\widetilde{M}_S$ from higher invariant mass bins are almost as good as the bounds from all the bins combined tells us that the deviations from the SM are greater as the invariant mass increases. We, therefore, need to consider the data in the invariant mass distribution as well. In this case, however, we need to consider $\sqrt{s}$ as high as possible, and hence the constant-λ approximation is no longer a good one. We must therefore perform our analysis using exact forms for $\lambda_s^{(d)}(x_s)$

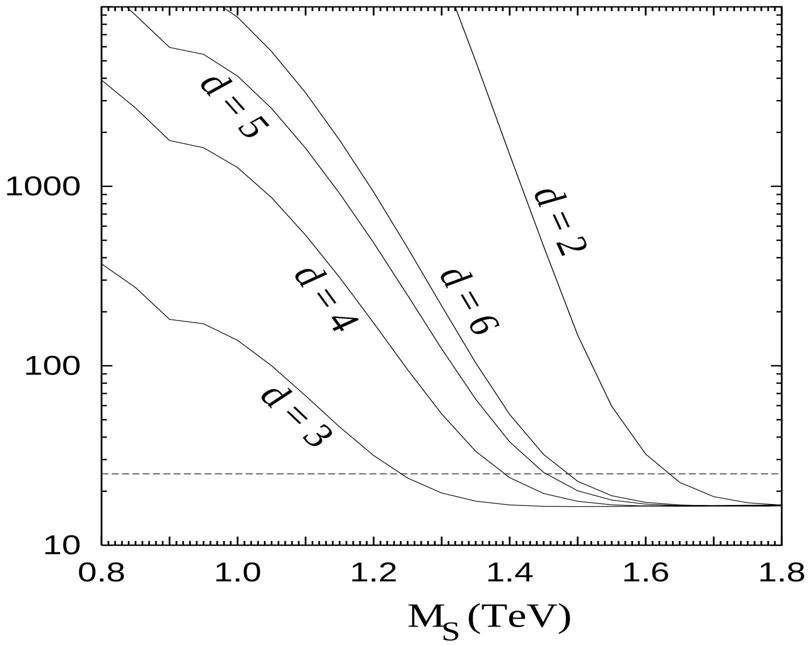

Figure 2: Illustrating the variation of χ^2 obtained by fitting the predictions of the graviton-exchange model with the D0 data on the dijet invariant mass, as a function of the string scale M_S. The dashed line represents the 95% C.L. value.

and $\lambda_t^{(d)}(x_t)$ and restrict ourselves to the formulation of the effective theory given in, for example, ref. [16]. Of course, this means that the bounds can no longer be expressed in terms of a single effective $\widetilde{M}_S$, but must be worked out separately for each case $d = 2, 3, 4, 5$ and 6.

We use the published dijet mass distributions from the D0 experiment [32] for our analysis. The D0 Collaboration has presented data for the dijet invariant mass in 15 bins covering the range from 200 GeV to 1 TeV. These data, like those on the angular distribution, are very well fitted by the SM predictions and hence can be used to bound new physics effects. We do this by performing a simple binwise χ^2-fit of the predictions of the graviton-exchange model (using the cuts used by the D0 experiment) to the data for each value of d, and find the value of M_S (not $\widetilde{M}_S$) which corresponds to a 95% C.L. effect. Our results are shown in figure 2.

In figure 2, we plot the χ^2 value as a function of the string scale M_S for each value of d, as solid lines. It is clear that the χ^2 drops sharply from very high values (this is a reflection of the fourth-power suppression) to a common asymptotic value which corresponds to the SM. For the lower values of M_S, the fit includes only those bins for which $\sqrt{\hat{s}} < M_S$: this accounts for the kinks in some of the graphs around 900 GeV to 1 TeV. The horizontal dashed line corresponds to the 95% C.L. value for 15 bins, and hence, the corresponding bounds on M_S can be read off. These are listed in table 2. The weakest of these bounds is for $d = 3$, which may be easily explained by referring to figure 1, where it is clear that the ratio $\mathcal{R}$ is the smallest

No. of extra dimensions	$d = 2$	$d = 3$	$d = 4$	$d = 5$	$d = 6$
Lower bound on M_S	1695	1235	1390	1450	1485

Table 2: 95% C.L. limits on M_S (in GeV) derived from the dijet mass distribution.

in this case. However, even this compares favourably with other bounds on M_S from terrestrial experiments, while the bounds for the other values of d are significantly better. We can make bold to say, therefore, that a study of dijet production at the Tevatron yields the best collider bounds on M_S using *currently available* data.

Finally, we mention some limitations of the present analysis. In itself, the use of a parton-level Monte-Carlo generator does not create much of an error, since the putative jets (here represented by the parent partons) are mostly well-separated. However, effects of initial and final state radiation need to be convoluted with the present cross-sections. The statistical analysis is based on a simple-minded χ^2 fit of our predictions to the data and could certainly be refined. Having said this, however, we wish to remind the reader of the extremely strong dependence of the cross-sections on M_S, i.e. $\sigma \propto M_S^{-4}$ at the least. As a result of this, a 10% change in the cross-section changes a bound of $M_S > 1\,\mathrm{TeV}$ by not more than about $25\,\mathrm{GeV}$, which is roughly the same order as the uncertainty induced by the spread in the experimental data. We conclude, therefore, that the bounds on M_S derived in this work are quite robust.

We have studied the implications of large extra dimensions and a low effective quantum gravity scale for dijet production at the Tevatron. Virtual exchange of the Kaluza-Klein states are considered and the sensitivity of the experimental cross-sections to this interesting new physics is studied. We find that this process allows us to put very stringent limits on the string scale M_S — in fact, of all processes with virtual graviton exchanges considered so far, these bounds are by far the best. To obtain these bounds, we have considered the angular distributions and the mass distributions. The resulting limits from the second of these observables are better because they involve higher energies, where the graviton couplings are stronger. At the Run II of the Tevatron, due to the higher luminosities that will be available, we expect that M_S values of the order of 2–2.5 TeV can be probed in dijet studies. Jet production at significantly higher energies, such as those which will become available at the LHC, is able to probe the physics of large extra dimensions to much higher scales. These results will be presented in a future publication [27].

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