Dijet production at hadron colliders in theories with large extra dimensions

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We consider the production of high invariant mass jet pairs at hadron colliders as a test for TeV scale gravitational effects. We find that this signal can probe effective Planck masses of about 10 TeV at the CERN LHC with a center of mass energy of 14 TeV and 1.5 TeV at the Fermilab Tevatron with a center of mass energy of 2 TeV. These results are compared to analogous scattering processes at leptonic colliders.

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Conventionally, gravitation is assumed to have no effect on TeV scale interactions since the Planck mass $M_P = G_N^{-1/2} = 1.22\times 10^{19}$ GeV is well above this scale. The fact that M_P is so large in comparison to the standard model (SM) electroweak scale of $O(100\,\mathrm{GeV})$ does, however, lead to the so called hierarchy problem as in the absence of intervening physical scales, fine tuning of the parameters of the SM at the Planck scale are required to keep the electroweak scale small.

Motivated by the fact that many string theories such as M theory [1] can only be consistent if there are more than 3+1 dimensions (the extra dimensions forming a compact manifold), it has been recently suggested [2,3] that gravity may become strong at the TeV scale. In particular, if there are n compact dimensions of length R, at distances $d<R$ the Newtonian inverse square law will fail [2] and the gravitational force will grow at a rate of $1/d^{n+2}$. If R is sufficiently large, even the weak strength of gravitational force at the macroscopic scale can lead to a strong force at distances of $1\,\mathrm{TeV}^{-1}$. The size of the extra dimension required is $8\pi R^n M_S^{2+n} \sim M_P^2$ where M_S is the effective Planck scale of the $(4+n)$-dimensional theory. Since M_S is not far beyond the electroweak scale, the hierarchy problem is eliminated.

For instance, if $n=1$ and $M_S=1$ TeV, then R is of the order of 10^8 km, large on the scale of the solar system and clearly ruled out by astronomical observations. However, if $n\geqslant 2$ and $M_S\geqslant 1$ TeV then $R<1$ mm; there are no experimental constraints on the behavior of gravitation at such distance scales [4]. This compactification is thus not ruled out based on gravitational experiments.[1]

Of course, in these theories all other forces and particles appear to exist in the usual $(3+1)$-dimensions. In the proposed scenario of [2] this results from the existence of a (3+1) dimensional brane to which all known fermions and gauge fields are confined in the total of $(3+n+1)$-dimensional space. Only gravitation can propagate through the bulk and therefore may directly be sensitive to the effects of the new dimensions and the onset of gravitational effects would be evident at collisions of energy M_S.

To calculate such perturbative gravitational effects, we adopt the 4-dimensional point of view. Thus, we interpret the graviton states which move parallel to the 4 dimensions of space time as the usual massless graviton. The graviton states with momentum components perpendicular to the brane are observed as a continuum of massive objects. The density of graviton states is given by [2,3,6,7]

$$\rho(m^2) = \frac{dN}{dm^2} = \frac{m^{n-2}}{G_N M_S^{n+2}} \tag{1}$$

where m is the mass of the graviton.

Gravitons with polarizations that lie entirely within the brane are effective spin 2 objects while scalar or vector states result if the polarizations are partially or completely perpendicular to the brane. In this paper, we will be concerned with the effects dominated by the exchange of virtual spin 2 gravitons.

To perform perturbative calculations in this theory, Feynman rules for the coupling of graviton states to ordinary particles can be formulated where $\kappa=\sqrt{16\pi G_N}$ is the expansion parameter [6,7]; in particular, we adopt the conventions of [7].

In the case of the exchange of virtual graviton states, one must add coherently the effect of each graviton. In the case of an s-channel exchange, the propagator is proportional to $i/(s-m_{G_\lambda}^2)$ where m_{G_λ} is the mass of the graviton state G_λ. Thus, when the effects of all the gravitons are taken together, the amplitude is proportional to

$$\sum_\lambda \frac{i}{s-m_{G_\lambda}^2} = D(s). \tag{2}$$

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[1]There are however alternative schemes which can consistently allow one extra dimension such as in [5].

TABLE I. In this table, we give the value of k_s and the functions $f(z)$, $g(z)$ and $h(z)$ which define the differential cross section in Eq. (6) for each of the $2\to 2$ processes relevant to dijet production in hadron collisions. The variable z is the scattering angle in the center of mass frame given by $(t-u)/s$ and in all cases the total cross section is given by integrating z over the range $-1\leqslant z\leqslant +1$. Note that the differential cross section for $q\bar{q}\to gg$ is (64/9) times the differential cross section given in this table.

Process	k_s	$f(z)$
$q\bar{q}\to q'\bar{q}'$	1/36	$8(1+z^2)$
$qq'\to qq'$; $q\bar{q}'\to q\bar{q}'$	1/36	$16\frac{5+2z+z^2}{(1-z)^2}$
$qq\to qq$	1/72	$\frac{32}{3}\frac{(z^2+11)(3z^2+1)}{(1-z^2)^2}$
$q\bar{q}\to q\bar{q}$	1/36	$\frac{8}{3}\frac{(7-4z+z^2)(5+4z+3z^2)}{(1-z)^2}$
$gg\to q\bar{q}$	1/256	$\frac{16}{3}\frac{(9z^2+7)(1+z^2)}{1-z^2}$
$gq\to gq$	1/96	$\frac{32}{3}\frac{(5+2z+z^2)(11+5z+2z^2)}{(1+z)(1-z)^2}$
$gg\to gg$	1/512	$288\frac{(3+z^2)^3}{(1-z^2)^2}$

Process	g(z)	h(z)
$q\bar{q}\to q'\bar{q}'$	0	$\frac{9}{256}(1-3z^2+4z^4)$
$qq'\to qq'$; $q\bar{q}'\to q\bar{q}'$	0	$\frac{9}{2048}(149+232z+114z^2+16z^3+z^4)$
$qq\to qq$	$-4\frac{5-3z^2}{1-z^2}$	$\frac{3}{1024}(547+306z^2+3z^4)$
$q\bar{q}\to q\bar{q}$	$-\frac{1}{4}\frac{(11-14z-z^2)(1+z)^2}{1-z}$	$\frac{3}{2048}(443+692z+354z^2+116z^3+107z^4)$
$gg\to q\bar{q}$	$-4(1+z^2)$	$\frac{3}{8}(1-z^4)$
$gq\to gq$	$2(5+2z+z^2)$	$\frac{3}{8}(1+z)(5+2z+z^2)$
$gg\to gg$	$120(3+z^2)$	$\frac{9}{4}(3+z^2)^2$

If $n\geqslant 2$ this sum is formally divergent as m_{G_λ} becomes large. We assume that the distribution has a cutoff at $m_{G_\lambda}\sim M_S$, where the underlying theory becomes manifest. Taking this point of view, the value of $D(s)$ is calculated in [6,7]:

$$\kappa^2 D(s) = -i\frac{16\pi}{M_S^4}F + O\left(\frac{s}{M_S^2}\right). \tag{3}$$

The quantity F contains all the dependence on n and is given by

$$F=\begin{cases}\log(s/M_S^2) & \text{for } n=2,\\ 2/(n-2) & \text{for } n>2.\end{cases} \tag{4}$$

In a $2\to 2$ process, a similar expression will apply for t and u channel exchanges. If $n>2$, $D(s)$ is independent of s in this approximation and likewise the sum of the propagators in the t and u channels will be identical. As pointed out in [8], this will not necessarily be a good approximation in the case of $n=2$ because of the logarithmic dependence of D on s.

The theory formulated in this way does not treat the cutoff in detail but makes the *ad hoc* assumption that the cutoff is M_S. However, bounds which are obtained in this way may be applied to a more specific theory by computing an effective M_S which would follow from the parameters of a given theory. We can thus investigate the phenomenology which may occur at various colliders [8,9] as well as precision experiments [10]. An example of a scenario where the cutoff $O(M_S)$ is realized in a natural way from recoil effects of the brane is discussed in [11]. In this picture, the cutoff is related to the stiffness of the brane illustrating that in general, the cutoff can result from new physics manifest at M_S.

To place limits on such theories at a hadron collider, it is natural to consider the production of real gravitons. If such gravitons were produced in association with a jet, the monojet + large missing P_T signal should be unmistakable. Indeed this process was considered in [12] where it was found that a bound of $M_S=1.3$, 0.9, 0.8 TeV may eventually be achieved at the Tevatron for $n=2$, 4 and 6. At the LHC these bounds may be extended to $M_S=4.5$, 3.4 and 3.3 TeV. The analogous process at the Next Linear Collider (NLC), $e^+e^-\to\gamma G$ ($G=$graviton), was also considered in [12,13] giving a reach at $\sqrt{s}=1$ TeV of $M_S=7.7$, 4.5 and 3.1 TeV for $n=2$, 4 and 6. Slightly better bounds may be obtained in the case of an $e\gamma$ collider with the reaction $e\gamma\to eG$ [14].

In processes which produce real gravitons, the cross section is proportional to $(E/M_S)^{n+2}$ so less stringent bounds can be placed on M_S at large n. Stringent astrophysical constraints have also been found for $n=2$ both from the rate of supernova cooling [15,16] which gives $M_S>30$ TeV and also the absence of a diffuse cosmic gamma ray background from relic gravitons [15,17], which gives $M_S>130$ TeV. The latter bound, depends strongly on the assumption that all the decay of the graviton is dominated by perturbative modes.

In contrast to real graviton production which gives stringent bounds when $n=2$, virtual graviton exchange which we consider here in the case of $pp\to 2$ jets$+X$ or $p\bar{p}\to 2$ jets $+X$ gives similar bounds for all n as can be seen from Eq. (4). It should also be kept in mind that these theories imply the existence of new physics at the scale of M_S which may also lead to two jet processes, such as discussed in [18]. Thus, in experimentally probing the two jet signal, one can only place limits on the gravitational effects common to all such models.

At the parton level, two jet events are generated via processes of the form $\rho_1\rho_2\to\rho_3\rho_4$, where ρ_l are partons (of momentum p_l). In particular, the possible parton level processes are as follows:

$$\begin{aligned}
&(a)\ \ q\bar{q}\to q'\bar{q}' \quad (b)\ \ qq'\to qq'/q\bar{q}'\to q\bar{q}'\\
&(c)\ \ qq\to qq \quad (d)\ \ q\bar{q}\to q\bar{q}\\
&(e)\ \ gg\to q\bar{q}/q\bar{q}\to gg \quad (f)\ \ gq\to gq/g\bar{q}\to g\bar{q}\\
&(g)\ \ gg\to gg,
\end{aligned} \tag{5}$$

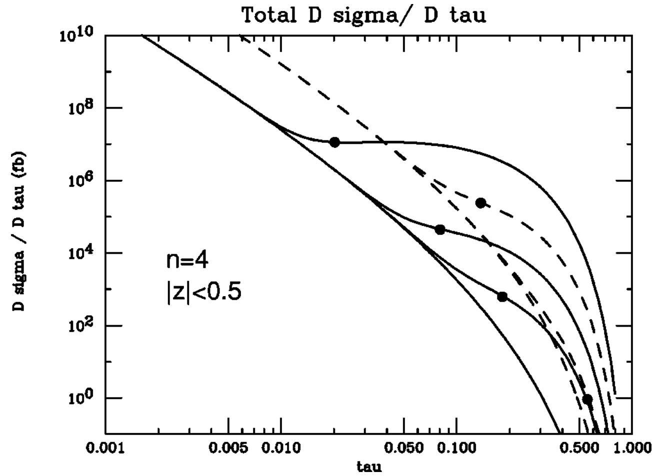

FIG. 1. The total differential cross sections $d\sigma/d\tau$ are shown as a function of τ for $n=4$ where the acceptance cut $|z|\leq 0.5$ has been imposed for various values of M_S. Solid lines represent the contribution at the LHC ($\sqrt{s_0}=14$ TeV) if $M_S=2$ TeV (upper solid line), 4 TeV, 6 TeV and the standard model alone (lower solid line). The dashed lines represent the contributions at the Tevatron ($\sqrt{s_0}=2$ TeV) if $M_S=0.75$ TeV (upper dashed line), 1.5 TeV and the standard model alone (lower dashed line). The circles indicate where $M_S^2=\tau s_0$.

where q represents some flavor of quark and $q'\neq q$ is a distinct flavor.

Of course each of these scattering processes has a SM contribution which the gravitational amplitudes will interfere with (where allowed by color conservation). We shall see however that since the amplitude grows with s^2, scattering through gravitons tends to be harder and is easily separated from SM processes which drop with s.

The tree-level hard cross-sections σ_i for a given subprocess i, including the gravitational effects and their interference with the SM, can be written in the form:

$$\frac{d\sigma_i}{dz}=k_s\left[\frac{\pi\alpha_s^2}{2s}f(z)-\frac{2\pi\alpha_s F}{s}\frac{s^2}{M_S^4}g(z)+\frac{8\pi F^2}{s}\frac{s^4}{M_S^8}h(z)\right] \tag{6}$$

where $z=p_1\cdot(p_4-p_3)/p_1\cdot p_2$ is the center of mass scattering angle and $s=(p_1+p_2)^2$. In the limit where the mass of the quarks is neglected, the formulas for $f(z)$, $g(z)$ and $h(z)$ and k_s are given in Table I where the SM part agrees with the calculations given for example in [19]. Note that in cases where there are two identical particles in the final state, a factor of 1/2 is included in k_s so in all cases phase space should be integrated over the range $-1\leq z\leq +1$.

The total differential two jet cross section is shown in Fig. 1 at the CERN Large Hadron Collider (LHC) with $\sqrt{s_0}=14$ TeV, for $M_S=2$, 4, 6 TeV and at the Fermilab Tevatron $p\bar{p}$ collider with $\sqrt{s_0}=2$ TeV, for $M_S=0.75$, 1.5 TeV; Fig. 1 also shows the prediction from the SM alone. Here, s_0 is the square of the center of mass energy of the hadronic collision and $\tau=s/s_0$. In all cases we have imposed the cut $|z|<0.5$ which tends to favor the graviton scattering processes. The fraction of this differential cross section due to

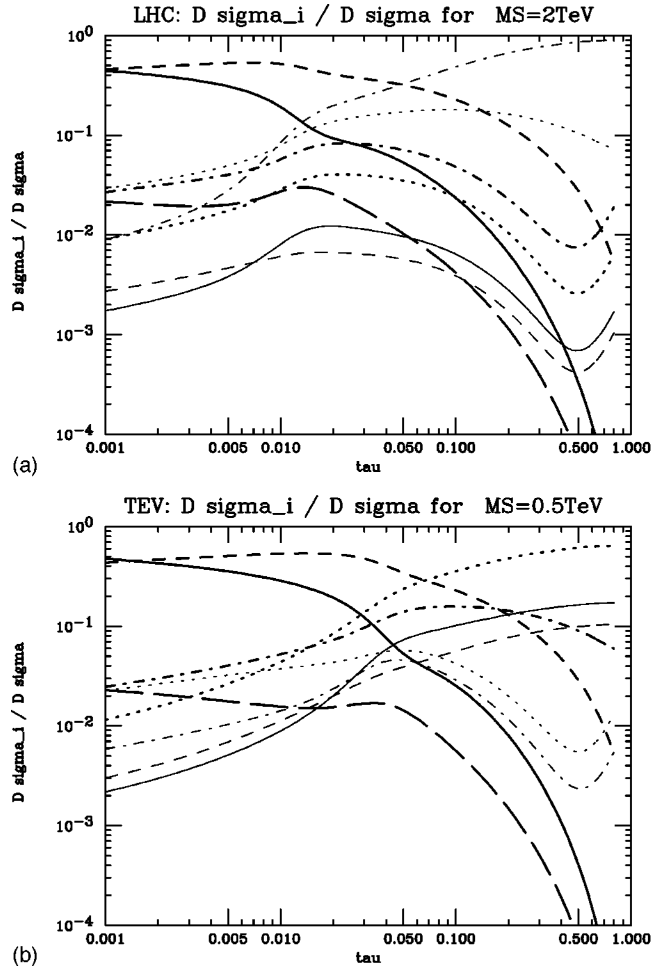

FIG. 2. $(d\sigma_i/d\tau)/(d\sigma/d\tau)$ as a function of τ for each partonic mode with $n=4$ is shown; in (a) the LHC is considered with pp collisions at $\sqrt{s_0}=14$ TeV taking $M_S=2$ TeV while in (b) the results for the Tevatron is considered with $p\bar{p}$ collisions at $\sqrt{s_0}=2$ TeV taking $M_S=0.5$ TeV. In both cases a cut of $z<0.5$ is imposed. The subprocesses are $q\bar{q}\to q'\bar{q}'$ (thin dashed line); $qq'\to qq'$ (thin dotted line); $q\bar{q}'\to q\bar{q}'$ (thick dot dash line); $qq\to qq$ (thin dot dash line); $q\bar{q}\to q\bar{q}$ (thick dotted line); $gg\to q\bar{q}$ (thick long dashed line); $q\bar{q}\to gg$ (thin solid line); $qg\to qg+\bar{q}g\to\bar{q}g$ (thick dashed line); $gg\to gg$ (thick solid line).

various partonic subprocesses for the LHC with $M_S=2$ TeV and at the Tevatron with $M_S=0.5$ TeV is shown in Figs. 2(a) and 2(b). Of course, the extrapolation of these curves beyond M_S is not valid since at that point new physical processes, such as the brane recoil effects in [11], will enter and suppress the effect. In Fig. 1 this point is indicated by the black circles and so the portion of the curve to the right of the circles may depend on the cutoff mechanism. In these results we have used the CTEQ4M structure functions, set 1 [20].

In the case of the LHC, one can see that the dominant contributions are from $gg\to gg$ and $qg\to qg$ for $\tau<0.1$, which results from the dominance of gluons for lower τ. At $\tau>0.1$, $qq\to qq$ becomes important due to the hard component of the structure functions of the constituent quarks. At the Tevatron, $gg\to gg$ and $qg\to qg$ are dominant at low τ while here $q\bar{q}\to q\bar{q}$ will be dominant at larger τ.

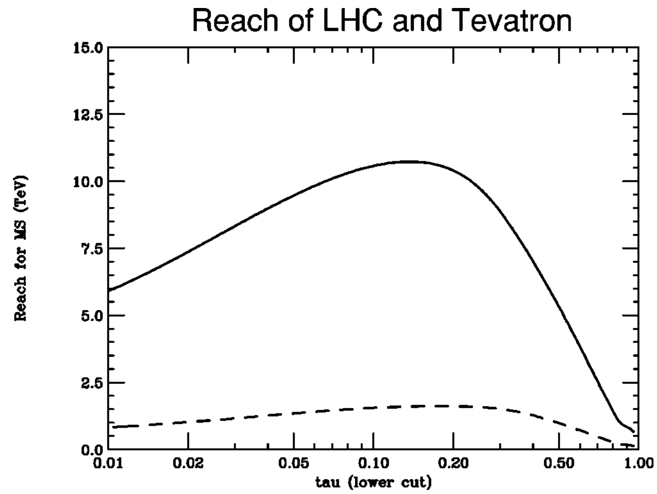

FIG. 3. The reach of the Tevatron (dashed line) and LHC (solid line) in the case of $n=4$ as a function of a lower cut in τ based on the total cross section as in Fig. 1. In both cases a criterion of 3 sigma was used. In the LHC case an integrated luminosity of $30\,\mathrm{fb}^{-1}$ was assumed while in the case of the Tevatron an integrated luminosity of $2\,\mathrm{fb}^{-1}$ was assumed.

In order to get an idea of what the reach of these signals are, we consider imposing cuts of the form $\tau>\tau_0$ since, clearly, the SM backgrounds are more important at lower τ. In Fig. 3 we show the maximum value of M_S for which the difference between the standard model and the standard model with gravitation has a 3σ significance both at the LHC and at the Tevatron. In this graph we have taken an integrated luminosity for the LHC of $30\,\mathrm{fb}^{-1}$ and for the Tevatron of $2\,\mathrm{fb}^{-1}$. From this graph it is apparent that, for an optimal τ_0 cut of ~ 0.2, the LHC reach according to this criterion is ~ 10 TeV, while, for the Tevatron it is ~ 1.5 TeV. A study [21] of existing Collider Detector at Fermilab (CDF) and D0 two jet data gives a bound of $M_S>1.2$ TeV.

A related process which has been previously considered [22] is the Drell-Yan process at hadron colliders, pp or $p\bar{p}\to e^+e^-+X$. In that case, at a $\sqrt{s_0}=14$ TeV LHC, with integrated luminosity of $30\,\mathrm{fb}^{-1}$, one obtains a reach of about 5.6 TeV, while at the Tevatron with $\sqrt{s_0}=2$ TeV, given an integrated luminosity of $2\,\mathrm{fb}^{-1}$ one obtains a reach of 1.3 TeV.

It is interesting to compare these two jet results to those which may be obtained at the NLC by studying $2\to 2$ scattering processes. Many such processes have been considered in the literature [22–24]. In particular it was pointed out in [24] that the $e^-e^-\to e^-e^-$ mode does somewhat better than the e^+e^- modes at the same luminosity. For the sake of definiteness, let us consider the reach of a e^+e^- or e^-e^- collider with $\sqrt{s}=1$ TeV and integrated luminosity of $100\,\mathrm{fb}^{-1}$, where we impose a cut on the two final state particles of $|z|<0.5$. In this case we find that the reach in M_S is 7 TeV for $e^+e^-\to\mu^+\mu^-$, 4 TeV for $e^+e^-\to 2$ jets, 5.5 TeV for $e^+e^-\to\gamma\gamma$, 8.5 TeV for $e^+e^-\to e^+e^-$ and 9.2 TeV for $e^-e^-\to e^-e^-$.

Another proposed mode of operation of an NLC is to convert it into a gamma-gamma collider by scattering optical frequency laser beams off of the electron beams [25]. This allows, for instance the study of $\gamma\gamma\rightarrow\gamma\gamma$, where there is no tree level SM background. The leading SM contribution is given by the box diagram discussed in [26]. These processes were studied extensively in [8,27] where in [8] detailed consideration is given to optimization of the cuts and polarization of the photons and the electrons. A reach of 3.5 TeV is thus obtained for $n=6$ and likewise 3.8 TeV for $n=4$ based on an NLC with electron-positron center of mass energy $\sqrt{s_{ee}}=1$ TeV. Of course one may also consider a NLC where only one of the electron beams is converted into a photon beam. At such a collider, one may study $e^{\pm}\gamma\rightarrow e^{\pm}\gamma$. For this process a reach of $M_S\sim 7.5$ TeV is found [28], again for $n=4$ based on an NLC with electron-positron center of mass energy $\sqrt{s_{ee}}=1$ TeV and an integrated luminosity of $100\,\mathrm{fb}^{-1}$.

The case of two photons going to two jets, $\gamma\gamma\rightarrow q\bar{q}$ and $\gamma\gamma\rightarrow gg$, has been considered in detail in [29]. They find that in a $\gamma\gamma$ collider based on a 500 GeV electron-positron machine, the sensitivity is (3.2,2.8) TeV for $n=(4,6)$ while the sensitivity is (11.1,9.4) TeV at a 2 TeV machine.

In conclusion then, two jet signals at the LHC can give a reach of about 10 TeV for M_S which is quite favorable compared to limits which may be obtained via Drell-Yan (5.8 TeV) and monojet signals (i.e. 4.5; 3.3 TeV for $n=2$; 6). An NLC collider running in e^-e^- mode could achieve comparable reaches i.e., 8.5 TeV; however, it is unclear if such a collider would run extensively in this mode. In e^+e^- mode, of the processes considered, the reaction $e^+e^-\rightarrow e^+e^-$ gives the best reach of 6.8 TeV. Even though there are large SM backgrounds to the dijet cross section at hadronic colliders, the fact that graviton exchange dominantly contributes only at the highest values of τ makes this signal viable.

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