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# Single Kaluza Klein Production in Universal Extra Dimensions

C. Macesanu[1,†,‡], S. Nandi[2,†,♯] and M. Rujoiu[3,†,*]

†*Department of Physics, Oklahoma State University*
*Stillwater, Oklahoma, 74078*
‡*Department of Physics, Syracuse University*
*Syracuse, New York 13244*
♯*Fermi National Accelerator Laboratory*
*P.O. Box 500, Batavia, Il 60510*[4]
**Institute of Space Sciences, Bucharest-Magurele*
*Romania, 76900*

**Abstract**

In the universal extra dimensions models, Kaluza Klein excitations of matter are generaly produced in pairs. However, if matter lives on a fat brane embedded in a larger space, gravity-matter interactions do not obey KK number conservation, thus making possible the production of single KK excitations at colliders. We evaluate the production rates for such excitations at the Tevatron and LHC colliders, and look for ways to detect them.

## 1 Introduction

In ADD-type models [1], the 4D universe we live in is viewed as a brane in a space with 4+N dimensions. Gravity can propagate in all dimensions, while matter fields (and the gauge bosons) are restricted on the 4D brane. As a consequence, the gravity field will appear to an observer on the Standard Model brane as consisting of a massless graviton plus an infinite number of Kaluza-Klein modes, with mass spacing proportional to the inverse length of the extra dimensions. Based on arguments of naturalness (that is, the fundamental gravity scale

[1]Email address: mcos@pas.rochester.edu
[2]Email address: shaown@okstate.edu
[3]Email address: mrujoiu@okstate.edu
[4]S.N. was participant in the Summer Visitor Program at Fermilab.

in 4+N dimensions should be close to the electroweak scale), the mass splitting of the KK gravitons range from $10^{-3}$ eV order (for N = 2) to MeV order (for N = 6).

One might consider modifying the above scenario by letting the matter fields propagate into one or more extra dimensions. Then ordinary matter will also have KK exciations with masses of order $1/R$. Noting that no such excitations have been seen at colliders, one should conclude that $R$ should be at least of inverse TeV order. However, we then have to change our picture about gravity, by either assuming that the extra dimensions are asymmetrical [2] (some of sub-millimeter order, in which only gravity propagate, and some of order inverse TeV, in which matter can also propagate) or, if we keep all compact dimensions of $\text{TeV}^{-1}$ size, by reintroducing some hierarchy between the gravity and electroweak scales.

Perhaps a more satisfying picture would be one in which the gravity sector is unaffected (the same as in ADD), but matter propagates only in part of the extra dimensions. In other words, the 4D brane on which Standard Model matter lives is endowed with a finite thickness in the extra-dimensions, resulting in what is known as the 'fat brane' scenario [3]. We also assume that all the Standard Model matter fields live on this fat brane, like in Universal Extra Dimensions (UED) models [4].

The consequences of this scenario for phenomenology are quite interesting. In the standard UED models, the first level KK excitations are stable (due to KK number conservation and mass degeneracy at tree level), therefore they are rather hard to see at colliders. In the fat brane scenario, KK number conservation is broken in the gravity-matter interactions, so these first level KK excitations can decay by radiating a graviton. Since there is a large number of gravitons with mass less than the TeV scale, the gravitational decay width of these particles is large enough that the decay takes place inside the detector, and the experimental signal will be jets plus missing energy [5]. Moreover, if radiative corrections alter the massess of the first level excitations [6, 7], an even richer phenomenology can ensue, with photons as well as leptons as end products of the decays of the heavy KK excitations [8, 9].

However, besides consequences for the decay of KK matter excitations, gravity interactions can also mediate production of a single KK excitation in colliders. This is unlike the usual case in the UED scenario, where KK matter excitations are produced in pairs. Since production of a pair of heavy particles is often kinematically restricted, one might then envision the case where it will be easier to produce a single KK excitation (provided that the gravitational interaction is strong enough). The study of this possibility is the purpose of this paper.

The outline of the paper is as follows. In the next section we will give a brief overview of the model under consideration, together with the analytic expressions for the square amplitudes of the relevant processes. In section 3 we present the cross-sections for the production of one jet + one excited KK state in the UED model with a fat brane, at the Tevatron and Large Hadron Collider (LHC). We also look at the dependence of the signal cross-section (jets + missing energy) on cuts on relevant observables, and compare the signal with the Standard Model background. We end with conclusions.

# 2 Model description

In our scenario, matter propagates in one compact extra dimension, which, in order to accomodate the chiral fermions of the Standard Model (SM), is an $S_1/Z_2$ orbifold with a radius $R$ of order inverse TeV. As a consequence of orbifolding, the SM scalar and gauge boson fields aquire each one KK excitation tower (the modes being even under the $Z_2$ parity), while each SM fermion field aquire two KK excitation towers (the tower correponding to the left handed fermions being different than the tower associated with the right handed fermions) [4, 5]. The masses of the particles in these towers are, at tree level, multiples of $M = 1/R$.

The space in which matter propagates is embeded as a fat brane ([3]) in a larger space of $4+N$ dimensions where gravity propagates. The length $r$ of these extra dimensions is given in terms of the fundamental Plank scale $M_D$ by the ADD relation:

$$M_{Pl}^2 = M_D^N \left(\frac{r}{2\pi}\right)^{N+2},$$

where $M_{Pl}$ is the usual Plank scale in 4 dimensions. The interactions between matter and gravity in this model have been worked out in [11]. The Feynman rules for matter-gravitation interactions are quite similar to those obtained for the case of matter propagating into 4 dimensions only [10], except that each vertex is multiplied by a form-factor

$$\mathcal{F}^c_{lm|n} \sim \frac{1}{\pi R}\int_0^{\pi R} dy \cos\left(\frac{ly}{R}\right)\cos\left(\frac{my}{R}\right)\exp\left(2\pi i\frac{ny}{r}\right)$$

which describe the superposition in the fifth dimension of the graviton and matter wave functions.

Having matter and gravity propagate on different scales in the fifth dimension means that KK number conservation will not hold for gravity-matter interactions. This has two consequences: first is that the first level KK excitations of matter will decay to SM matter radiating a graviton. Since there is a whole KK graviton tower which can mediate this decay, the decay width (evaluated in [11], for example ) is large enough that any KK excitation of matter produced at colliders will decay inside the detector[5]. The phenomenology resulting from these decays has been studied in [5].

The second consequence is that it is also possible to produce a single KK excitation of matter (unlike the usual UED case, where these excitations are produced in pairs). This will take place through the exchange of gravitons; again, since there is a large number of graviton excitations, the contribution coming from all of these can be big enough to offset the $1/M_{pl}$ scale coupling of the individual graviton. The phenomenology resulting from this scenario leads to interesting signals for the extra dimensions, and is discussed in the following.

## 2.1 Single KK production

We give here the analytic expressions for the squared amplitudes for the processes contributing to the production of one KK excited state of matter. We use the following modified

[5]In this paper we will consider only the gravitational decays of the matter KK excitations, neglecting decays due to mass splittings. This is justified by the fact that the gravitational decay width increases as (mass)$^3$, and the KK states used in our analysis are rather heavy.

Mandelstam variables:

$$s = 2p_1p_2 \ , \ t = -2p_1p_3 \ , \ u = -2p_1p_4$$

where $p_1, p_2$ are the momenta of the initial state partons, and $p_3, p_4$ the momenta of the final state ones. $D(s), D(t)$ and $D(u)$ are the summed graviton propagators (see next section) in the $s, t$ and $u$ channels.

With these notations, the amplitudes for the relevant proceses are (we denote by a $^*$ the KK excitation of a SM particle):

1. for $q\bar{q} \to g^*g$ ($s$ channel only):

$$\bar{\sum}|M(q\bar{q} \to g^*g)|^2 = \frac{1}{3}tu(t^2+u^2) * D(s)^2$$

2. for $gg \to g^*g$ ($s, t$ and $u$ channels):

$$\bar{\sum}|M(gg \to g^*g)|^2 = \frac{1}{18}[(t^4+u^4) * D(s)^2 + (s^4+u^4) * D(t)^2 + (s^4+t^4) * D(u)^2 + 2u^4 * D(s) * D(t) + 2t^4 * D(s) * D(u) + 2s^4 * D(u) * D(t)]$$

3. for $qg \to qg^*$ and $\bar{q}g \to \bar{q}g^*$ ($t$ channel only):

$$\bar{\sum}|M(qg \to qg^*)|^2 = -\frac{1}{12}su(s^2+u^2) * D(t)^2$$

4. for $gg \to q^*\bar{q}$ ($s$ channel):

$$\bar{\sum}|M(gg \to q^*\bar{q})|^2 = \frac{1}{96}tu(t^2+u^2) * D(s)^2$$

5. for $q\bar{q} \to q^*\bar{q}$ and $q\bar{q} \to q\bar{q}^*$:

$$\bar{\sum}|M(q\bar{q} \to q^*\bar{q})|^2 = \frac{1}{256}[(s^4 - 10s^2tu + 32t^2u^2) * D(s)^2 + (t^4 - 10t^2su + 32s^2u^2) * D(t)^2 - 2u^2(4u^2+9st) * D(s) * D(t)]$$

6. for $qq \to q^*q$ and $\bar{q}\bar{q} \to \bar{q}^*\bar{q}$:

$$\bar{\sum}|M(qq \to q^*q)|^2 = \frac{1}{256}[(t^4 - 10t^2su + 32s^2u^2) * D(t)^2 + (u^4 - 10u^2st + 32s^2t^2) * D(u)^2 - 2s^2(4s^2+9tu) * D(t) * D(u)]$$

7. for $qg \to q^*g$:

$$\bar{\sum}|M(qg \to q^*g)|^2 = -\frac{1}{24}su(s^2+u^2) * D(t)^2$$

Also, the averaged squared amplitudes for scattering processes with different flavor quarks in the initial state ($q\bar{q}' \to q^*\bar{q}'$ and $qq' \to q^*q'$) are given by the $t$ channel contributions only from the corresponding expressions (5) and (6) above.

## 2.2 Summed propagator

The effective propagator for gravity mediated KK production is obtained by summing over all graviton excitations up to a cut-off $M_D$. Thus,

$$D(s) = \kappa^2 \sum_{\vec{n}} \mathcal{F}_{0|n_5} \frac{i}{s - m_{\vec{n}}^2} (\mathcal{F}^c_{1|n_5})^* , \tag{1}$$

where $\kappa = \sqrt{16\pi/M_{Pl}^2}$ is the 4D gravitational coupling constant, and $\mathcal{F}_{0|n_5}$ and $\mathcal{F}^c_{1|n_5}$ are form factors describing the interaction of the gravitons with the matter excitations on the brane ([11]). Note that terms in numerator of the propagator for a single graviton proportional to $p^\mu, p^\nu$ ([10]) drop out due to the fact that one end of the propagator couples always to two massless fermions. Hence the Lorenz structure of the propagator for the spin-2 massive graviton is simply:

$$B(k)_{\mu\nu,\rho\sigma} = \left( \eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \frac{2}{3}\eta_{\mu\nu}\eta_{\rho\sigma} \right) D(k^2) .$$

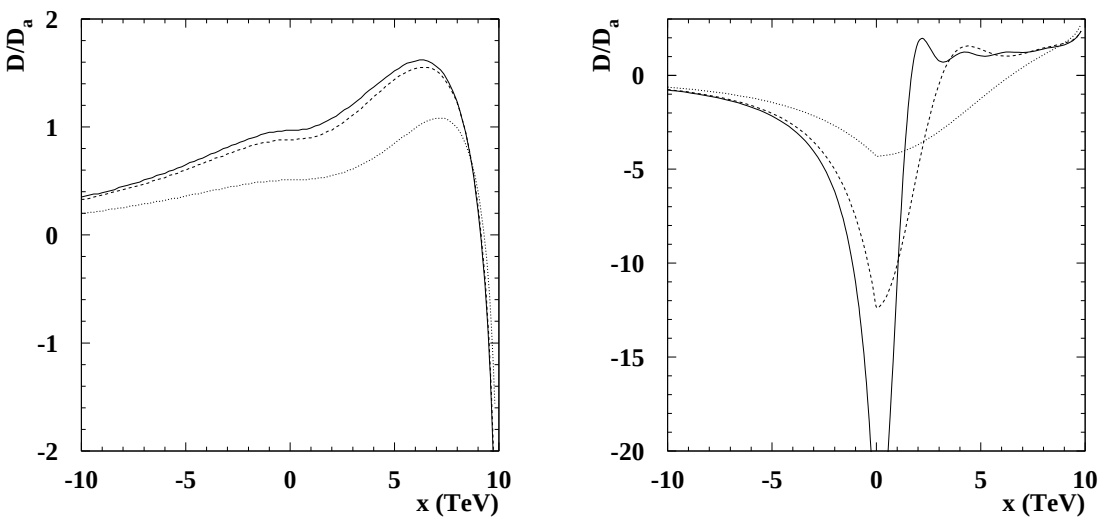


Figure 1: Ratio of values for exact propagator versus analytic approximation, for $N = 6$ (left) and $N = 2$ (right) extra dimensions. Here $M_D = 10$ TeV. Lines correspond to values for $M$ of 1 TeV (straight) 2 TeV (dashed) and 5 TeV (dotted line). On the horizontal axis is $x = \text{sign(s)}\sqrt{|s|}$.

In the limit where $s, M \ll M_D$, the sum (1) has been evaluated in [11]:

$$D(s) \simeq V_{N-1} \frac{16}{N-3} \frac{M}{M_D^5} \frac{2\sqrt{2}}{\pi^2} \int_0^{\pi M_s/M} \frac{\sin x}{1 - x^2/\pi^2} dx . \tag{2}$$

For the purposes of this paper, we evaluate (1) numerically, for each value of $s$ and $M_D$. It turns out that the approximate result (2) it is reasonably accurate, except for the cases

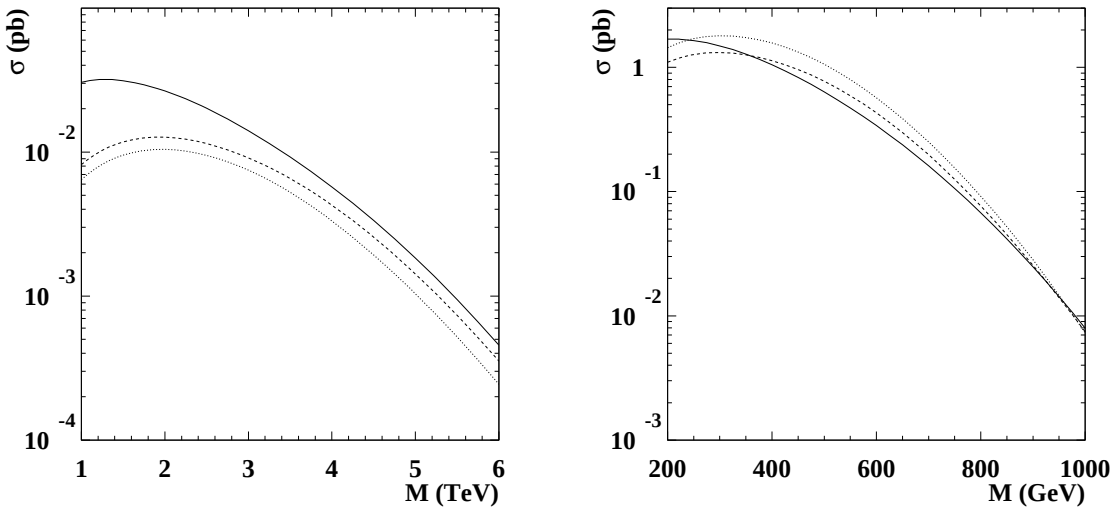


Figure 2: Production cross-sections at the LHC (right) and Tevatron RunII (left), for $N = 2$ (straight line), 4 (dashed line) and 6 (dotted line) extra dimensions.

$N = 2, 3$ (when strictly speaking it is not applicable). In Fig. 1 we print the ratio between the exact summed propagator (obtained by numerical integration) and the analytic approximation (2); negative values of $s$ are applicable for the case of $t$ and $u$ channel scattering.

# 3 Results

The cross-sections for the gravity mediated production of one KK excitation at LHC and Tevatron Run II are given in Fig. 2. As one can see, due to the fact that only a single heavy particle has to be produced, the reach of these machines has the potential to be quite large. Note, however, that the magnitude of the cross-section depends critically on the magnitude of the fundamental Planck scale $M_D$ (the value of this parameter in Fig. 2 is set to $M_D = 10$ TeV for the LHC simulation and $M_D = 1.5$ TeV for the Tevatron one). This can be understood from Eq. (2); since the propagator depends on the 5th power of $M_D$, this means that the production cross-section will scale as $(1/M_D)^{10}$. Therefore, a doubling of the fundamental gravity scale will reduce this cross section by roughly three orders of magnitude.

From Fig. 2, we see then that, at the LHC, there is a significant signal if the $M_D$ scale is around 10 TeV or lower, for masses of the KK excitations of matter as high as 5 TeV. However, in order to make a discovery, one has to see the signal over the Standard Model background. Since in this case the final state consist of two partons and the graviton produced in the decay of a heavy KK state, the experimental signal will be two jets plus missing energy. The SM background will then get contributions from Z + 2 jets processes (where Z decays to $\nu\bar{\nu}$ or $\tau\bar{\tau}$ pairs), W + 2 jets (with the lepton from the W decay unidentifiable), $t\bar{t}$ production, with one top decaying to $b\bar{\nu}l$ and unidentified lepton and jets, and QCD multijet

production with mismeasured $\not{E}_T$. In order to be able to eliminate this background, one must use cuts on the physical observables.

It is therefore interesting to consider our signal's dependence on cuts on jet transverse momentum and the missing energy in an event. These distributions are presented in Fig. 3. We see that due to the large mass of the KK particle being produced, the transverse momentum of the jets is quite large. This also holds even more for the missing energy; it is interesting to note that due to the fact that the invisible momentum goes all in one direction (there is a single graviton escaping) the missing energy distribution is harder than it would be in the case with two invisible particles in the final state (which is the case for KK pair production).

We can assume then that by requiring a large transverse momentum and an even larger missing transverse energy one will be able to get a good signal/background ratio. We will use the following type of cuts: $p_{1T}, p_{2T} > p_T^{\rm cut}$, $\not{E}_T > n p_T^{\rm cut}$, with n = 1, 2, 3. We also include a cut on rapidity $|y| < 4$ in our analysis, and we require that the two observable jets be separated by a cone with $R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.4$. In Fig. 4(left) we plot the signal as a function of $p_T^{\rm cut}$, for $M = 3$ TeV, $M_D = 10$ TeV and $N = 6$.

With such large cuts on the transverse momentum and missing energy, the dominant backgrounds come from Z + 2 jets production and possibly QCD processes. Previous estimates of this background [12] seem to indicate that for n = 1 and $p_T^{\rm cut} > 400$ GeV the magnitudes of these two contributions are about the same. However, one might suspect that as we increase the magnitude of the cut on the missing energy, the backgrounds due to mismeasurement in QCD processes will decrease, and the dominant one will become the Z

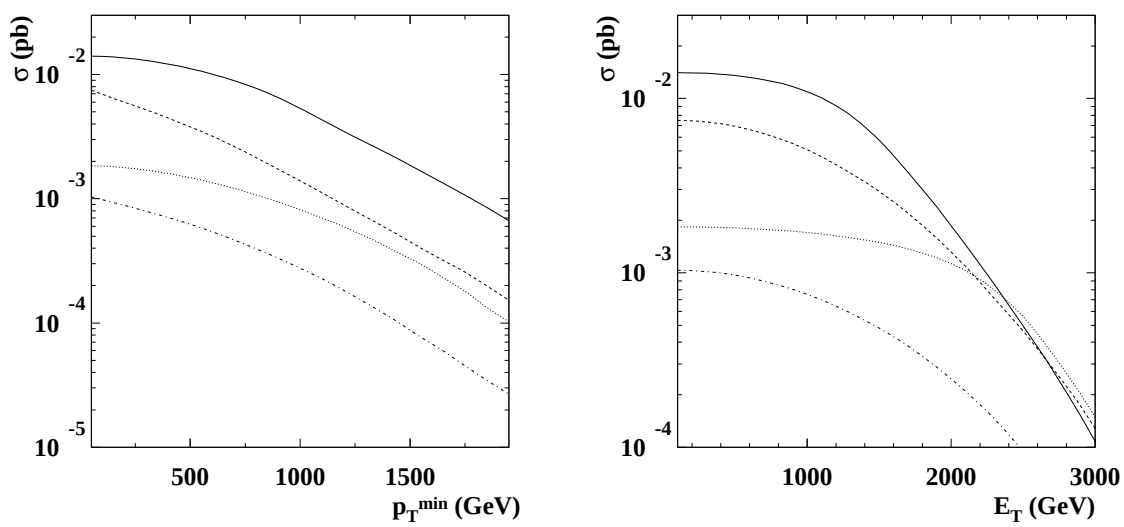


Figure 3: Cross section as function of cuts on the minimum $p_T$ of jets (left) and missing energy $\not{E}_T$ in an event (right). Straight and dashed line correspond to $M = 3$ TeV ($N = 2$ and $N = 6$ respectively) while dotted and dash-dotted lines correspond to $M = 5$ TeV (again, for $N = 2$ and $N = 6$).

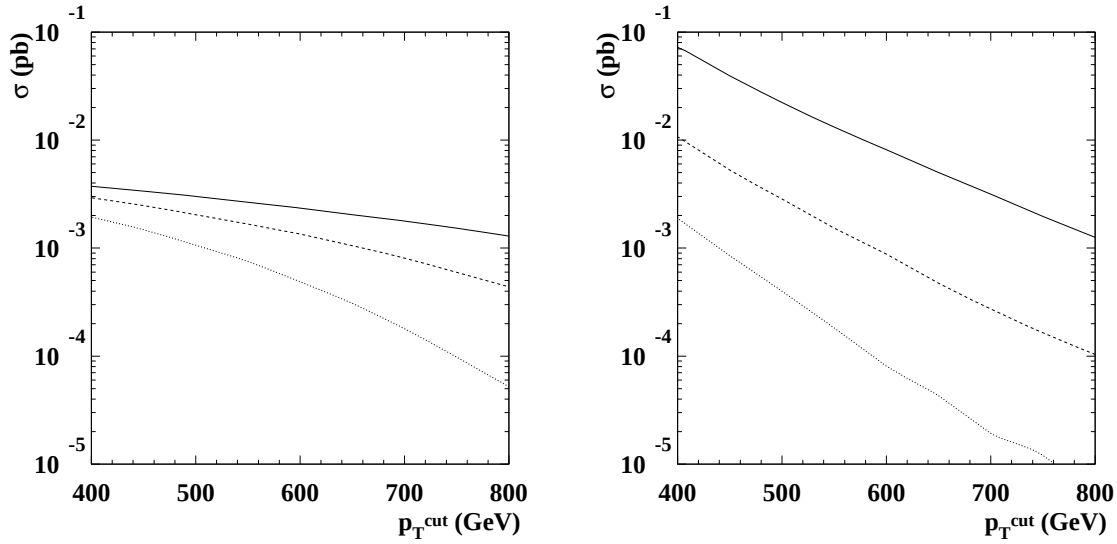


Figure 4: Signal(left) and backround(right) dependence on the parameter $p_T^{\rm cut}$. The three lines correspond to n = 1 (straight), 2 (dashed) and 3 (dotted line). Cuts on rapidity and jet separation are also implemented.

+ 2 jets. This reasoning is supported by the analysis in [13], which at large missing energy shows a faster drop in the $\not{E}_T$ distribution for QCD processes than for the Z + 2 jets. We therefore assume the the Z+ 2 jets process to be our entire background, and we evaluate it at parton level with the help of the MadEvent generator [14]. The dependence of the background on the parameter $p_T^{\rm cut}$ is plotted in Fig. 4(right), with the same kinematical cuts as used for the signal.

From this figure one can see that taking either one of the following choice of cuts: a) $p_T^{\rm cut} = 600$ GeV and $n = 3$, or b) $p_T^{\rm cut} = 800$ GeV and $n = 2$, the background will be $\sim 10$ events for an integrated luminosity of 100 fb$^{-1}$ at LHC. In Fig. 5 we plot the contour lines in the $M - M_D$ plane corresponding to the signal being 20 events (straigh line for $N = 6$ and dashed line for $N = 2$) and 100 events (dotted line for $N = 6$ and dotdashed line for $N = 2$) at the same luminosity. The left plot in the figure was obtained using the a) set of cuts, while the right plot was obtained using the b) set of cuts. As noted before, the reach in $M$ can be large ( $\sim 6$ TeV) for low values of $M_D$, but it drops quite fast as $M_D$ decreases. We see from this plot that the most favorable case corresponds to $N = 2$, due to the fact that the production cross-section is larger, and also that the transverse momenta of the jets are stronger in this case.

One can do the same type of analysis for the Tevatron RunII. We find that a reasonable choice for the cuts on the jet transverse momenta and missing energy is $p_{1T}, p_{2T} > 150$ GeV, $\not{E}_T > 300$ GeV. With these cuts the Z + 2 jets background (which is the dominant one here, too [15]) is around one event, for an integrated luminosity of 2 fb$^{-1}$. In Fig. 6 we give the reach of the Tevatron Run II for 10 and 50 signal events, for the number of extra dimensions in which gravity propagates $N = 2$ and 6.

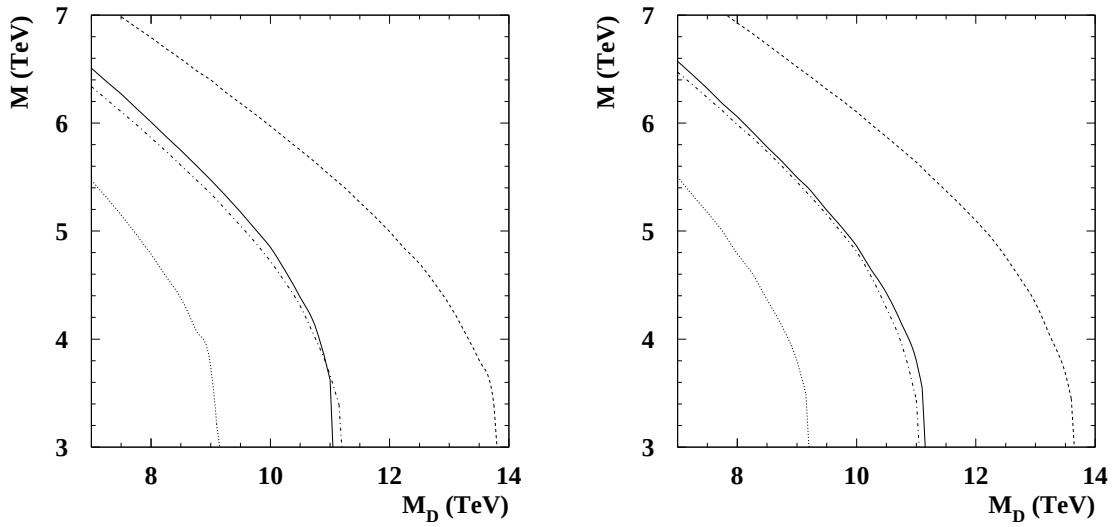


Figure 5: LHC reach for 20 and 100 signal events (straight and dotted lines corresponds to $N = 6$, and dashed and dotdashed line correspond to $N = 2$, respectively.) Cuts a) are used in the left panel, and b) in the right panel.

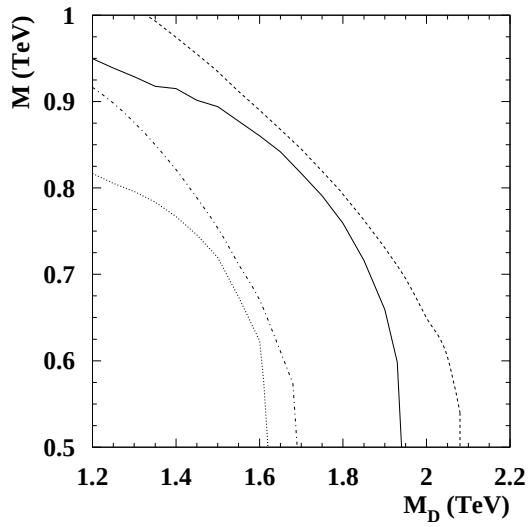


Figure 6: Tevatron Run II reach for 10 and 50 signal events (straight and dotted lines corresponds to $N = 6$, and dashed and dotdashed line correspond to $N = 2$, respectively.) Here we use cuts with $p_T^{\rm cut} = 150$ GeV and n = 2.

# 4 Conclusions

We discuss the gravity mediated production of single KK excitations of gluons and quarks at the Tevatron Run II and LHC. In standard Universal Extra Dimensions models, KK number

conservation requires these excitations to be produced in pairs, thereby requiring one to pay a large price in phase space. However, in our scenario, where matter fields propagate on a fat brane, the gravitational interaction does not obey KK number-conservation rules, allowing the production of a single KK excitation and increasing the possible reach in mass.

Thus, while for pair-produced KK excitations the LHC reach was found to be around 3 TeV [5], for gravity mediated single KK production the LHC reach can be as large as 7 TeV. However, the production cross-section is strongly dependent on the fundamental gravity scale $M_D$. We find out that in order for the production cross-section to be observable, the gravity scale $M_D$ should not be much larger than the scale $M$ which determines the mass of the matter KK excitations.

From an experimental viewpoint, what results is a picture in which one should look either for pair production of low mass KK excitations ($M = 1/R \lesssim 3$ TeV), or production of a single KK excitation for a higher value of the compactification scale $1/R$. The experimental signal will be two jets plus missing energy in both cases, but there will be subtle differences in the distribution of the physical observables: for example the missing energy distribution is likely to be harder in the later case. Adding the possibility of additional decay channels for the matter KK excitations (see, for example [9]) will further enhance the differences between the signal in the two cases, and enrich the phenomenology of KK matter production.

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# References

[1] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. **B429**, 263 (1998) and Phys. Rev. **D59**, 086004 (1999); I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. **B436**, 257 (1998); I. Antoniadis, Phys. Lett. **B246**, 377 (1990).

[2] J. Lykken and S. Nandi, Phys. Lett. B **485**, 224 (2000) [arXiv:hep-ph/9908505].

[3] A. De Rujula, A. Donini, M. B. Gavela and S. Rigolin, Phys. Lett. B **482**, 195 (2000) [arXiv:hep-ph/0001335].

[4] T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001) [arXiv:hep-ph/0012100].

[5] C. Macesanu, C. D. McMullen and S. Nandi, Phys. Rev. D **66**, 015009 (2002) [arXiv:hep-ph/0201300].

[6] H. Georgi, A. K. Grant and G. Hailu, Phys. Lett. B **506**, 207 (2001) [arXiv:hep-ph/0012379].

[7] H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 036005 (2002) [arXiv:hep-ph/0204342].

[8] H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 056006 (2002) [arXiv:hep-ph/0205314].

[9] C. Macesanu, C. D. McMullen and S. Nandi, Phys. Lett. B **546**, 253 (2002) [arXiv:hep-ph/0207269].

[10] T. Han, J. D. Lykken and R. J. Zhang, Phys. Rev. D **59**, 105006 (1999) [arXiv:hep-ph/9811350].

[11] C. Macesanu, A. Mitov and S. Nandi, Phys. Rev. D **68**, 084008 (2003) [arXiv:hep-ph/0305029].

[12] H. Baer, C. h. Chen, F. Paige and X. Tata, Phys. Rev. D **52**, 2746 (1995) [arXiv:hep-ph/9503271].

[13] I. Gaines, D. Green, S. Kunori, S. Lammel, J. Marraffino, J. Womersley and W. Wu, FERMILAB-FN-0642.

[14] F. Maltoni and T. Stelzer, JHEP **0302**, 027 (2003) [arXiv:hep-ph/0208156].

[15] H. Baer, C. h. Chen, F. Paige and X. Tata, Phys. Rev. D **54**, 5866 (1996) [arXiv:hep-ph/9604406].