New Signal for Universal Extra Dimensions

C. Macesanu\textsuperscript{\dag}, C.D. McMullen\textsuperscript{\dag,†} and S. Nandi\textsuperscript{\dag,†}

\textsuperscript{\dag}Department of Physics, Oklahoma State University
Stillwater, Oklahoma, 74078
\textsuperscript{†}Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Il 60510

Abstract

In the universal extra dimensions (UED) scenario, the tree level masses of the first level Kaluza-Klein (KK) excitations of Standard Model particles are essentially degenerate. Radiative corrections will, however, lift this degeneracy, allowing the first level excitations to decay to the lightest KK particle (LKP), which is the $\gamma^*$. KK number conservation implies that the LKP is stable. Then, since the SM particles radiated during these decays are rather soft, the observation of KK excitations production and decay in collider experiments will be quite difficult. We propose to add to this model KK number violating interactions mediated by gravity, which allow the $\gamma^*$ to decay to a photon and a KK graviton. For a variety a models and a large range of parameters, these decays will occur within the detector. Thus, pair production of KK excitations will give rise to a striking collider signal, consisting of two hard photons plus large missing energy (due to escaping gravitons). We evaluate the cross-section for these signals at the Tevatron and LHC, and derive the reach of these colliders in the search for universal extra dimensions.

1 Introduction

In the past years there has been a resurgence of interest in the phenomenological implications of models with extra dimensions. Such models appear naturally in the context of string theories. However, since the compactification scale is usually of order of the Planck mass, this was thought to have few, if any, direct implications for experiments at the current energy scale. Recent developements have led to the construction of models where the

\textsuperscript{1}Email address: mcos@pas.rochester.edu
\textsuperscript{2}Email address: mcmulle@okstate.edu
\textsuperscript{3}Email address: shaown@okstate.edu
\textsuperscript{4}Summer Visitor Program.
radius of the compact extra dimensions is of order inverse TeV, or even larger \[2\], with rich implications for the phenomenology of present day colliders \[3\].

In this paper we are concerned with an extension of the basic model proposed by Arkani-Hamed, Dimopoulos and Dvali (ADD) \[2\]. In this universal extra dimensions (UED) scenario \[4\], all the Standard Model (SM) fields, fermions as well as bosons, propagate in the bulk. This model has a number of interesting features, among which is the conservation of Kaluza-Klein (KK) number for interactions involving SM particles or their excitations. As a consequence, KK excitations can be produced only in pairs at colliders; also, tree-level corrections to SM processes are forbidden, making the search for extra dimensions that much more difficult. Some other features of this model are summarized in the following.

At tree level, the masses of the first level KK excitations are almost degenerate. The splitting between the first level masses is due to the SM mass terms, and is extremely small, except for particles with large SM mass. Therefore, at tree level most of the first level KK excitations would be stable in the UED scenario, due to KK number conservation. The parameters of this model may be subjected to restrictions due to cosmological constraints on the existence of a large number of stable massive particles. In order to bypass these restrictions, some mechanisms provide for the decays of these excitations through KK-number violating interactions mediated by gravity. Then, the experimental signature for producing KK excitations at Tevatron or the Large Hadron Collider (LHC) would be two jets plus large missing energy. An analysis of the phenomenological implications of this model in hadron collider experiments has been performed in \[5\]. The results obtained indicate that, based on Tevatron Run I data, the compactification scale can be as low as 350 GeV. Moreover, the Tevatron Run II can test for the existence of universal extra dimensions up to around 500 GeV, while the reach at LHC is about 3 TeV.

Loop corrections, however, can give important contributions to the masses of the KK particles, thus potentially invalidating the above analysis. For the UED model, these corrections have been evaluated in \[3\]. The result, dependent on some assumptions concerning the renormalization of boundary terms, is that the radiative corrections to the tree level masses are typically of order 10% for the strongly interacting particles (the heaviest one being the gluon) and of order few percent for the the leptons and electroweak gauge bosons (the photon being the lightest one). Naturally, the phenomenology of this model is quite different from the case discussed above. The excitations of the SM quarks and gluons produced at a hadron collider will cascade decay to the \(\gamma^*\), which is the lightest KK excitation. If this particle is stable, the experimental signature for this process will be the missing energy carried away by the \(\gamma^*\)'s, and the soft SM particles radiated away in the process of the cascade decays. The phenomenology of this model has been studied in \[7\]. The total energy of these particles will be of the order of the difference in mass between the KK particle which initiates the decay chain \(g^* \text{ or } q^*\) and the \(\gamma^*\), therefore they will be rather difficult to see in a hadron collider environment. Moreover, the transverse missing energy (which is the quantity experimentally accessible) is also small, making the rejection of SM backgrounds using this type of cuts quite difficult. The LHC reach for this model has been estimated in \[7\] to be about 1.5 TeV.

The aim of this paper is to analyze the case when both types of decays, gravity mediated and due to mass splitting, can occur. The experimental consequences of this model can be quite remarkable. For example, in the case when the decay widths of the first level KK
excitations due to mass splitting are much larger than the gravity mediated decay widths, the gluon and quark excitations produced at a hadron collider will cascade decay to $\gamma^*$, which in turn will decay to a photon and a KK graviton. The experimental signal in this case will be a striking two photon + missing energy event. Moreover, since the photons are coming from the decay of a heavy particle (the $\gamma^*$), their transverse momentum will be large, and the signal will be easy to separate from the SM background. The exact fraction of KK excitations decays leading to this kind of signal depends on the parameters of the model, and will be discussed in the following sections.

The outline of this paper is as follows. In the next section we review the essential features of the universal extra dimensions model at one loop. A mechanism for the gravity mediated decay of the first level KK excitations is also presented. In Section 3 we discuss the experimental consequences of the lightest KK particle (LKP) $\gamma^*$ decaying into a photon and a graviton, and we give the collider reach for the discovery of UED at the Tevatron and LHC in this scenario. We end with conclusions.

2 Universal Extra Dimensions

The UED scenario is an extension of the SM in which all particles, fermions as well as bosons, live in a $4 + \delta$ dimensional brane, which is potentially embedded in a larger space where only gravity propagates. In this model, momentum conservation along the extra dimensions dictates that the KK particles can be produced only in pairs. This would make them much harder to see at present and future colliders; the limits on the compactification scale of these extra dimensions are so far as low as a few hundred GeV [7, 5, 4].

While there are no a priori constraints on the number of universal extra dimensions, we shall consider only the simpler case when there is only one such dimension. For $\delta = 1$, obtaining the SM chiral fermions out of the zero modes of the 5-dimensional KK fields requires that the fifth dimension have an orbifold structure. For simplicity, this is usually taken to be $S_1/Z_2$. In this model, for each SM Dirac fermion $q$ there are two 5-dimensional fermionic fields: $q^\bullet$ and $q^\circ$. The first one is a doublet under SU(2), while the second one is a singlet. Moreover, the left handed part of $q^\bullet$ and the right handed part of $q^\circ$ are taken to be even under the $Z_2$ orbifold symmetry, while $q^\bullet_R$ and $q^\circ_L$ are taken to be odd under the same symmetry, therefore projecting out half the zero modes of each KK field. The remaining halves stand for the left and right-handed parts of the SM chiral fermion: $q_L = q^\bullet_0$, $q_R = q^\circ_0$.

The 4D interactions of the $n$th KK excitation of the $q^\bullet$ and $q^\circ$ fields with the SM gauge bosons are given by:

$$L_{q_nA} = -Q_n^\bullet \left\{ Qe \mathcal{A} X + \frac{g_2}{\cos \theta_W} \left( \frac{\tau_3^3}{2} - Q \sin^2 \theta_W \right) Z + \frac{g_2}{\sqrt{2}} \begin{pmatrix} 0 & W^+ \\ W^- & 0 \end{pmatrix} Q_n^\bullet \right\}$$

$$- \bar{q}^\circ_n Q \left( e \mathcal{A} X - \frac{\sin^2 \theta_W}{\cos \theta_W} Z \right) q^\circ_n$$

where $Q$ and $\tau_3$ are the charge and isospin of the corresponding fermionic field, $X$ is the SM photon field, and $\theta_W$, $e$ and $g_2$ are the SM Weinberg angle and the electromagnetic and SU(2) four-dimensional coupling constants.
At tree level, the masses of the KK excitations come primarily from the 5D kinetic energy terms, with a small contribution from the Higgs interaction (which gives mass to the zero-mode fields):

\[ m_n^2 = \frac{n^2}{R^2} + m_{SM}^2 \]

Since the compactification radius \( R \) is of order of several hundred GeV\(^{-1} \), this means that the masses at a given KK level are almost degenerate; KK number conservation thus implies that the first level excitations of light SM particles are stable. This degeneracy is, however, lifted by loop corrections \([6]\). The consequences of going beyond tree level can be thought of as being twofold. First, there are radiative corrections due to the fields propagating along the fifth dimensions (called bulk terms in \([3]\)). These corrections are well defined and finite, due to \( 1/m_n^2 \) suppression for heavier KK modes. For the fermionic fields they are zero, while for the gauge fields they are actually negative, and of order \( \alpha/R \). Second, loop effects induce boundary terms localized on the fixed points of the \( S_1/Z_2 \) orbifold \([6, 8]\). The coefficients of these terms depend on the fundamental theory at the Plank scale, and they are unknown in the low energy regime; moreover, the contributions to these terms coming from one loop corrections in the bulk are logarithmically divergent. Thus, it is necessary to introduce a cutoff scale \( \Lambda \); it is also necessary to specify an ansatz for the definition of unknown coefficients. We shall follow the choices made in \([6, 7]\); we refer the reader to these references for more details, and here we just summarize the results.

After taking into account the boundary terms contributions, the mass hierarchy between the first level KK excitations is as follows. The heaviest particle is the \( g^* \), which acquires a positive 20-to-30\% correction to its mass (depending on the choice of \( \Lambda \)). The next to heaviest particles are the excitations of the SM quarks, for which the mass correction is in the 20\% range. There is a small splitting between the mass of the \( q^* \) and \( q^0 \) quarks, due to differences in the electroweak interactions of the two fields. Since excitations of the top quark do not play a big role in our analysis, we can neglect the SM masses of the quarks involved. The rest of the first level KK excitations, arranged in order of decreasing mass, are the heavy gauge bosons \( W^* \) and \( Z^* \), the \( L^* \) excitations of the lepton and neutrino fields and the \( l^0 \) excitations of the same fields. The corrections to the masses of these particles are below 10\%. Finally, the lightest KK excitation is the \( \gamma^* \), whose mass does not change almost at all from tree level.

Due to the fact that the corrections to neutral U(1) and SU(2) gauge fields \( \delta m_{B_n} \) and \( \delta m_{A_n} \) are different, the mixing angle between these fields will not be the SM Weinberg angle anymore. In the limit when \( \delta m_{A_n}^2 - \delta m_{B_n}^2 \gg m_W^2 \), which generally holds for values of the compactification scale greater than 200 GeV, the \( n^{th} \) level mixing angle \( \theta_{W_n} \) will actually be very close to zero \([3]\). This means that the \( \gamma^* \) will be almost a pure \( B \) field; also, the fermions which are singlets under SU(2) (the \( q^0 \) and \( l^0 \)) will decouple almost completely from the SU(2) fields. The interaction between the electroweak gauge boson excitations and fermionic fields will be given by:

\[
\mathcal{L}_{q-A_n} = - \bar{Q} \cdot \chi_n \left[ Q_n \cos(\theta_{W_n} - \theta_{W}) + \tau_3 \sin(\theta_{W} - \theta_{W_n}) \right] - \bar{e_n} \left[ e_n \cos(\theta_{W} - \theta_{W_n}) \right]
\]
\[ + \frac{g_2}{\sqrt{2}} \left[ \begin{array}{cc} 0 & \mathbf{W}^+ \\ \mathbf{W}^- & 0 \end{array} \right] \right] P_L \mathbf{Q}_n - \sum \bar{q} e Q \left( \mathbf{X}_n \cos \theta_W - \mathbf{Z}_n \sin \theta_W \right) P_R \mathbf{q}_n + \text{h.c.} \]

These couplings, together with the mass hierarchy discussed above, dictates the following decay pattern for the excitations of quarks and gluons produced at a hadron collider (see also [7]). The \( g \) excitations will decay equally through the \( g_1^* \rightarrow q \bar{q}^* \) and \( g_1^* \rightarrow q q_1^0 \) channels (and the conjugate ones), where \( q \) can be any quark excluding the top, which is too heavy to be kinematically allowed. The singlet quark excitations \( q_1^0 \) will decay directly to the LKP: \( q_1^0 \rightarrow q \gamma^* \), since its coupling to the \( Z_1^* \) boson is suppressed. The decay of the doublet quark excitations \( q^* \) will proceed mostly through a three stages chain:

\[
q_1^* \rightarrow q Z_1^* \rightarrow q l l_1^* \rightarrow q l l \gamma^*, \quad \text{Br.} \sim 33\%, \quad \text{and} \]

\[
q_1^* \rightarrow q W_1^* \rightarrow q l' l_1^* \rightarrow q l' l \gamma^*, \quad \text{Br.} \sim 65\%
\]

where \( l \) and \( l' \) can be either a lepton or a neutrino. The branching ratios (Br.’s) for the intermediate \( Z_1^* \) and \( W_1^* \) decays to leptons are all approximatively equal to 1/6 (decays to quarks are not kinematically allowed). A small portion of the \( q_1^* \) decays (about 2%) also takes place directly to the LKP: \( q_1^* \rightarrow q \gamma^* \).

In absence of other interactions, the LKP in UED is stable. Then, the only signal of KK excitations production at a hadron collider will be missing energy in conjunction with soft leptons or jets radiated in the course of the decays of these excitations to the LKP. The phenomenological implications of this model have been studied in [7]. In this paper we aim to study the implications of having the LKP decay into a KK graviton and SM photon. Then, the experimental signal will be a striking two photon event with high \( p_T \), plus large missing energy and soft jets or leptons.

There are a number of models which allow for the gravity mediated decay of KK excitations [4, 9, 10]. As in [4], for illustration we will consider the specific case of a fat brane scenario [10]. In this model, the 4+1 dimensional space in which the UED fields live is a ‘fat’ brane in the 4+N dimensional bulk in which gravity propagates. The compactification scale of the bulk dimensions \( R_b \) is of order eV\(^{-1}\). Thus, in this model, the UED fields propagate a short way in the fifth dimension (the width of the brane \( \pi R \)), while gravity propagates all the way up to \( 2\pi R_b \). The couplings of the KK matter excitations with gravity are proportional with the overlap of their wave functions along the fifth dimension. The extra momentum along the \( y \) direction resulting from KK number violation is absorbed by the brane. The large density of states for the KK gravitons in the fifth dimension (the splitting between adjacent levels is of order eV) makes up for the smallness of the gravitational coupling, allowing the decay width of the matter KK excitations through this mechanism to be phenomenologically relevant (i.e., they decay within the detector). More details, as well as numerical results for these gravity mediated decay widths can be found in [4].

\footnote{Note, also, that the one-loop boundary terms may induce gravity-mediated LKP decays even in the absence of new physics. We plan to study this possibility in a further paper.}
3 Collider Signals

In this section we will discuss the possibility of discovery of UED KK excitations at the Tevatron and LHC. We start by assuming that the gravitational decay widths of the first level KK excitations are much smaller than the widths of the decays allowed by the mass splittings among these particles. This can happen for example in the fat brane scenario, if the number of extra dimensions in which gravity propagates is \( N = 6 \). Then, the only role of KK number violating gravity interaction is to mediate the decay of the \( \gamma^* \) obtained as a final result of the decays of gluon and quark excitations produced in the collision.  

Since the quarks and leptons radiated during the decay to \( \gamma^* \) are soft, the experimental signal for the production of a pair of KK excitations will be two photons plus a large amount of missing energy (taken away by the KK gravitons). The main backgrounds for this signal are multijet, direct photon, \( W + \gamma, W + \text{jets}, Z \rightarrow ee \) and \( Z \rightarrow \tau\tau \rightarrow ee \) events with misidentified photons and/or mismeasured \( \not{E}_T \). These backgrounds can be eliminated by using cuts on the transverse momentum of the photons and the missing energy.

The cross-sections for the \( \gamma\gamma X \not{E}_T \) signal coming from KK excitations production at Tevatron are presented in Fig. 1. On the horizontal axis is the compactification scale \( 1/R \). The solid line is the prediction for the Tevatron Run I (\( \sqrt{s} = 1.8 \) TeV), while the dashed line is the prediction for the Tevatron Run II (\( \sqrt{s} = 2 \) TeV). Here \( N \) is taken to be 6. These results also include cuts on photon \( p_T \) and \( \not{E}_T \) as described below.

Searches for new physics in the \( \gamma\gamma X \not{E}_T \) channel at Tevatron have been performed by the D0 and CDF collaborations [11, 12]. For example, imposing the kinematic cuts on the

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6In this analysis we neglect KK particles produced through weak interactions, since the cross-section is small.
Figure 2: Cross-sections for $\gamma\gamma X \not{E}_T$ signal coming from universal extra dimensions at LHC for $N = 6$ (solid line) and $N = 2$ (dashed line). The kinematic cuts applied are described in the text.

For the Tevatron Run I, the following cuts have been proposed in [13]: $p_T^{\gamma_1}, p_T^{\gamma_2} > 20$ GeV, $\not{E}_T > 25$ GeV. The SM background is $0.3 \pm 0.9$ events. The 5σ discovery cross-section with these kinematic cuts is about 4.5 fb with $2$ fb$^{-1}$ of integrated luminosity (Run IIA), or $1.2$ fb with $15$ fb$^{-1}$ integrated luminosity (Run IIB). Then, UED extra dimensions will be discovered at Run IIA if the compactification scale is smaller than about 490 GeV (520 GeV in Run IIB). On the other hand, assuming that the signal observed matches the predicted background, exclusion of the model at 95% CL can be achieved for $1/R < 510$ GeV at Run IIA, or $1/R < 540$ GeV at Run IIB.

Fig. 2 contains the cross-sections for $\gamma\gamma X \not{E}_T$ production through KK excitations at the LHC. The solid line corresponds to the case when there are $N = 6$ extra dimensions in which gravity can propagate, while the dashed line is the result for $N = 2$. The kinematic cuts on the momenta of the two hard photons are $p_T^{\gamma_1}, p_T^{\gamma_2} > 200$ GeV, $\not{E}_T > 200$ GeV. The SM background with these cuts is estimated in [14] to be roughly 0.05 fb. The 5σ discovery cross-section with 100 fb$^{-1}$ of integrated luminosity is then about 0.15 fb. We see that the
LHC can probe the compactification scale in this scenario up to 3 TeV.

The analysis presented so far applies to the case when the widths of the gravity mediated decays of the KK excitations are smaller than the widths of the decays of one KK excitation to another. With this condition, the results presented above are independent of the exact magnitude of these widths, and therefore on the exact parameters of the model. If the opposite case holds (that is, if gravity mediated decays dominate), then the experimental signal for the UED scenario will be two jets + missing energy. This case has been studied in [3]. If, on the other hand, the two sets of decay widths are roughly of the same order of magnitude, more complicated decay patterns can ensue. Hard leptons (from the decay of $q^*$) can also appear in the final state, along with a combination of photons and jets. The exact branching ratios depend on the parameters of the model.

Note that the magnitude of the decay widths of the KK excitations can depend quite strongly on the exact way the model is defined. The widths of decays among same level KK excitations depend on the masses involved, therefore on the cutoff scale $\Lambda$ (although this dependence is only logarithmic), and, maybe more importantly, on the assumptions made in fixing the unknown coefficients of the boundary terms. The widths of the gravity mediated decays depend, of course, on the exact mechanism which induces these decays. But even for a specific mechanism, let’s take the fat brane scenario as an example, they will depend on parameters like the number of dimensions in which gravity propagates ($N$), or on the fundamental Planck scale $M_D$. As a consequence, an analysis of the interplay between gravity and mass splitting effects in the decays of first level KK excitations is bound to be quite model dependent.

In the results presented below we will use the framework described in [6, 7] for the evaluation of the one loop mass corrections to the first level KK excitations. The cutoff scale $\Lambda$ is given by $\Lambda R = 20$, and the coupling constants are evaluated at the compactification scale. For the gravity sector we take $M_D = 5$ TeV, and present results for $N = 2$ and $N = 6$. The widths of the gravity mediated decays are evaluated in accordance with the formulas given in [6].

Fig. 3 (A and B) contains the values of the decay widths of first level KK excitations. The decay widths of gauge bosons are presented in 3A; the solid lines correspond to the gravity mediated decay widths for $N = 2$ (1) and $N = 6$ (2), while the dashed lines correspond to the widths of the decays due to mass splittings and gauge interactions: $g^* \rightarrow q\bar{q}^*, q\bar{q}^0 + \text{h.c.}$ (a), $W^* \rightarrow l\nu^*, l\nu^0 + \text{h.c.}$ (b), and $Z^* \rightarrow l\nu^* + \text{h.c.}$ (c). Fig. 3B contains the decay widths of the fermions; again the solid lines correspond to the gravity mediated decay widths for $N = 2$ (1) and $N = 6$ (2), while the dashed lines correspond to the widths of the decays $q^* \rightarrow q'W^*, qZ^*$ (a), $q^0 \rightarrow q\gamma^*$ (b) (this is the result for up-type quarks; the width for down-type quarks is four times smaller), and $l^* \rightarrow l\gamma^*$ (c) ($l^0$ is not produced in the decay of the quark and gluon excitations). These results can provide an estimate of what will be the main decay mode of the KK particles, and therefore what will be the experimental signal; for example, we see that if $N = 2$, gravity mediated decay will dominate, so we can expect two jets + $\not{E}_T$ in the final state; while if $N = 6$, the dominant signal for the UED model will be two photons + $\not{E}_T$ for values of compactification scale up to about 2.5 TeV.

In Fig. 4 we give the actual branching ratios for the $\gamma\gamma$ final state from the production of KK excitations. Note that these results not include only information about the relative
Figure 3: Decay widths for the first level KK excitations of gauge bosons (left) and fermions (right). The solid lines correspond to gravity mediated decays, with $N = 2$ (1) and $N = 6$ (2). The dashed lines correspond to decays allowed by mass splittings: $g^* \rightarrow qq^0 + \text{h.c.}$ (a), $W^* \rightarrow l\bar{\nu}^*, \nu l^* + \text{h.c.}$ (b), $Z^* \rightarrow l\bar{l}^* + \text{h.c.}$ (c) (left), and $q^* \rightarrow q'W^*, qZ^*$ (a), $q^0 \rightarrow q'\gamma^*$ (b), $l^* \rightarrow l\gamma^*$ (c) (right).

decay widths, but also information about the relative ratios of $q^0$ quarks, $q^*$ quarks and $g^*$ produced in the collision. (This is relevant since the $q^0$ quark, which decays directly to the

Figure 4: Branching ratios to final states: $\gamma\gamma$ (solid line), jet + $\gamma$ (dotted line) and lepton ($e$ or $\mu$) + $\gamma$ (dashed line) at the Tevatron Run II (left) for $N = 2$, and LHC (right) for $N = 6$. 
\( \gamma^* \), has a higher branching ratio to a final state containing a hard photon that the \( q^* \) or \( g^* \), which have to decay through a cascade.) Fig. 4A contains the \( \gamma\gamma \) branching ratio for \( N = 2 \) at low compatification scale (this branching ratio is 1 for \( N = 6 \)), while Fig. 4B shows the \( \gamma\gamma \) branching ratio for \( N = 6 \) at higher compatification scale (the branching ratio being 0 for \( N = 2 \) here). For completeness we also include the branching ratios to jet+\( \gamma X \) \( \not{E}_T \) and l\( \gamma X \) \( \not{E}_T \) final states, where \( l \) is a hard e or \( \mu \) coming from the gravity mediated decay of its first KK excitation, and \( X \) stands for the soft particles radiated during the decay chain.

4 Conclusions

Large universal extra dimensions models have exciting implications for the phenomenology of future colliders. In this paper we have studied a model where the signal for UED is an excess of two photon events (plus missing \( \not{E}_T \)) at hadron colliders. This final state arises naturally in the context when: a) mass splitting between the first level KK excitations allows the the gluon and quark excitations produced in the initial collision to cascade decay to the LKP (which is the \( \gamma^* \)); and b) gravity mediates the KK number violating decay of the LKP into a hard photon, which shows up in the detector, and a graviton, which is not observed. The condition for this chain of events to take place is that the widths for mass splitting mediated decays of the KK excitations be larger than the widths of the gravity mediated decays (while the latter ones are sufficiently large that the \( \gamma^* \) decay happens in the detector). We discuss a specific realization of this model, where the one loop masses of KK particles are computed in the framework used by Cheng, Matchev and Schmaltz in [6, 7], and gravity mediated decays take place in the fat brane scenario described in [5].

For cases when all the gluon and quark excitations decay to the LKP first, Tevatron Run I data sets a 380 GeV lower limit on the compactification scale for the UED. Run II will be able to probe for extra dimensions to 500 GeV with 2 pb\(^{-1}\) and 540 GeV with 15 pb\(^{-1}\), while the LHC reach is about 3 TeV. Limits in this channel will be correspondingly weakened when gravity mediated decays of \( g^* \) and \( q^* \) also play some role. If these decays dominate, the search for UED excitations should take place in the two jets plus missing \( \not{E}_T \) channel, as analyzed in [5].

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