Monojet and Single Photon Signals from Universal Extra Dimensions

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Abstract

The usual universal extra dimensions scenario does not allow for single production of first level Kaluza-Klein (KK) excitations of matter due to the KK number conservation. However, if the matter fields are localized on a fat brane embedded in a higher dimensional space, matter-gravitation interactions violate KK number, and the production of single KK excitations becomes possible. In this paper we analyze the production of a single KK matter excitation together with a graviton in the final state, and study the potential for discovery at the Tevatron and Large Hadron Collider.

1 Introduction

Some of the more interesting developments in modern particle physics are based on the idea that our universe has more dimensions than the four already known. Moreover, there may be reasons to believe that the size of these extra dimensions is rather large \cite{1,2} (maybe as large as inverse eV size), since then one could understand the weakness of gravitational interaction in contrast with the other fundamental forces. This in turn can have interesting implications for the phenomenology of present day and near-future colliders.

The experimental signatures of such models depend on the fields which propagate in extra dimensions (the bulk). In the simplest case, the ADD scenario \cite{2}, only gravity propagates in the extra dimensions. Our universe is viewed as a 4D-brane embedded in a bigger 4+N
dimensional space. In this picture, matter fields and gauge bosons are confined to the brane, gravity is naturally weak because it is propagating in \( N \) extra compact dimensions, and the hierarchy problem is resolved by bringing the fundamental scale of gravity close to the electroweak scale according to the formula:

\[
M^2_{Pl} = M_D^N \left( \frac{r}{2\pi} \right)^{N+2}.
\]

Here \( M_{Pl} \simeq 10^{19} \) GeV is the Plank scale in 4 dimensions, while \( M_D \) is the new fundamental scale of gravity in \( 4+N \) dimensions. One can see that with \( M_D \) of order TeV, one would obtain \( r \) as large as \( \text{eV}^{-1} \) (for \( N = 2 \)) up to \( \text{MeV}^{-1} \) (for \( N = 6 \)). A general feature of this type of models is the existence of the KK towers of excited states of the graviton. The mass splitting between levels is proportional to the inverse of the compactification radius \( \Delta m = \frac{2}{r} \).

One can construct extensions of the above model where matter fields also propagate in extra dimensions \[3\]. For the case when all matter fields propagate in the bulk, one obtains the universal extra dimensions scenario (UED) \[4\]. This scenario has several interesting features, which derive from the existence of a selection rule that requires KK number conservation for interactions. This means that the KK excitations have to be pair-produced, and, moreover, they cannot decay directly to the SM particles. The resulting phenomenology is then somewhat similar to that of supersymmetric theories \[6\] with almost degenerate superpartner masses (the mass splittings between the first lever KK excitations being generated by radiative corrections \[5\]). The lightest KK particle (LKP) is similar to the lightest supersymmetric particle (LSP) and is a possible dark matter candidate \[7\].

Although interesting, the simplest UED scenario described above leaves some questions unanswered. Since experiments have not detected any KK excitations of matter yet, the radius of the extra dimensions in which matter propagate must be at least of order of \( 10^{-1} \) TeV. But this would spoil the features the gravity sector had in the ADD-like models and would reintroduce a hierarchy between the electroweak and the gravity scale. Of course, one can introduce asymmetric models containing sub-millimeter size extra dimensions in which only gravity propagates and \( 10^{-1} \) size extra dimensions in which only matter propagates (see, for example, \[8\]). But we will not pursue that possibility here.

In this work, we consider the case in which the gravity sector has the same features as the ADD models (sub-millimeter size compact extra dimensions), but matter can propagate only distances of order \( 10^{-1} \) TeV along them. This is the fat-brane scenario \[9\], which preserves the ADD solution to the hierarchy problem, as well as give rise to new interesting low-energy phenomenology associated with production of KK matter excitations. Having UED on a fat brane allows gravity-matter interactions to break the KK number conservation.

As a consequence, the KK excitations of matter can decay via gravitational radiation (massless graviton as well as KK graviton emissions). If the LKP is the excitation of the photon, this will lead to signals with two high transverse momentum photons and missing energy in the final state \[10\]. Also, although the gravitational decay width of these particles is very small when considering only one graviton, the total width increases substantially when one considers the contribution from the large number of gravitons with masses from an eV (or MeV) all the way to a TeV. In fact, the gravitational decay widths may be large enough
so that the KK excitations decay mostly to SM quarks and gluons plus gravitons, rather than to the LKP. The experimental signature in such a case, assuming KK pair-production, would be two jets plus missing energy. The resulting phenomenology has been studied in [11].

A 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 can take place in two ways; either through the exchange of virtual gravitons, or with the production of a real graviton in the final state. In the first case, a SM quark or gluon is produced together with a KK excitation in the final state; the expected signals for such processes are two large $p_T$ jet events plus missing energy [12]. In the second case, which constitute the topic of the present paper, one will have a graviton in the final states together with a single KK excitation or a SM quark or gluon. This type of processes has as signature monojet events (or single photon, if the KK excitation decays to the LKP first), with large missing energy.

The outline of the paper is as follows. In the next section we will give a brief overview of the model used, comprising the matter and gravity sectors. In section 3 we comment on some interesting features of the production cross-sections for the relevant processes. One such feature is an enhancement of the cross section for very light gravitons in the final state. In section 4 we discuss the phenomenological signals for the production of one graviton plus one excited KK state (or a SM quark or gluon) in the UED model with a fat brane, at the Tevatron and LHC. We end with conclusions.

2 Model description

In our scenario, matter propagates on a fat brane with four Minkowsky plus one compact extra dimensions. The length scale $R$ of the compact dimension is of order TeV$^{-1}$. In order to have as zero modes only the SM content and to project out all other additional (unwanted) zero modes, we impose a $S_1/Z_2$ orbifold symmetry. This fat brane lives in a higher dimensional space (the bulk) in which only gravity propagates; the radius of these extra dimensions can be as large as eV$^{-1}$, and it is related to the 4D Planck mass $M_{Pl}$ by the ADD relation [11].

The 4 + $N$ dimensional graviton is expanded in KK modes [13]:

$$\hat{h}_{\hat{\mu}\hat{\nu}}(x, y) = \sum_{\vec{n}} \hat{h}_{\vec{n}\hat{\mu}\hat{\nu}}(x) \exp \left( \frac{2\pi \vec{n} \cdot \vec{y}}{r} \right).$$

(2)

The ‘hat’ denotes quantities which live in 4+$N$ dimensions: $\hat{\mu}, \hat{\nu} = 0, \ldots, 3, 5, \ldots 4 + N$, while $\mu, \nu = 0, \ldots, 3$. At each KK level we have the decomposition of the $\hat{h}_{\hat{\mu}\hat{\nu}}$ field into 4D tensor $h_{\mu\nu}$, $N$ vectors $A_{\mu i}$ and $N(N+1)/2$ scalar fields $\phi_{ij}$ by:

$$\hat{h}_{\vec{n}\hat{\mu}\hat{\nu}} = V_N^{-1/2} \left( h^{\vec{n}\mu\nu} + \eta_{\mu\nu} \phi^{\vec{n}} A^{\vec{n}}_{\mu i} A^{\vec{n}}_{\nu j} \right).$$

(3)

where $V_N = r^N$ is the volume of the $N$-dimensional torus. Not all these fields are indepen-
dent; by imposing the de Donder gauge fixing condition
\[ \partial \hat{\epsilon} \hat{h}_{\mu \nu} - \frac{1}{2} \hat{\eta}_{\mu \nu} \hat{h} = 0 , \]  
(4)
together with \( n_i A_{\mu i}^a = 0, n_i \phi_{ij}^a = 0 \), one can eliminate the spurious degrees of freedom and express the Lagrangian at each KK level \( \bar{n} \) in terms of one physical massive spin 2 field \( \tilde{h}_{\mu \nu} \), \( N - 1 \) massive vector gravitons \( \tilde{A}_{\mu i}^a \) and \( N(N-1)/2 \) massive scalars \( \tilde{\phi}_{ij}^a \). The vector and scalar physical fields also satisfy \( n_i \tilde{A}_{\mu i}^a = 0, n_i \tilde{\phi}_{ij}^a = 0 \).

Where the gravity is not affected in any way by orbifolding, the matter fields are. The corresponding decompositions for fermions, scalars and gauge bosons are:
\[ Q = \frac{1}{\sqrt{\pi R}} \left\{ Q_L + \sqrt{2} \sum_{n=1}^{\infty} \left[ Q^n_L \cos \left( \frac{ny}{R} \right) + Q^n_R \sin \left( \frac{ny}{R} \right) \right] \right\} , \]
\[ q = \frac{1}{\sqrt{\pi R}} \left\{ q_R + \sqrt{2} \sum_{n=1}^{\infty} \left[ q^n_R \cos \left( \frac{ny}{R} \right) + q^n_L \sin \left( \frac{ny}{R} \right) \right] \right\} , \]
\[ (\Phi, B^a_{\mu}) = \frac{1}{\sqrt{\pi R}} \left[ (\Phi_0, B^a_{\mu,0}) + \sqrt{2} \sum_{n=1}^{\infty} (\Phi_n, B^a_{\mu,n}) \cos \left( \frac{ny}{R} \right) \right] . \]
(5)

Here \( Q(q) \) are the 5D fermionic doublets (singlets) under SU(2) whose zero mode are the usual SM fermionic doublets (singlets); \( \Phi \) is the scalar field (Higgs) and \( B^a_{\mu} \) are the vector (gauge) fields. We work in a gauge where \( B^a_5 = 0 \) [14, 15]. The fields in (5) have the following parities under \( Z_2(y \rightarrow -y) \):
\[ Q_L(x, y) = Q_L(x, -y), \quad Q_R(x, y) = -Q_R(x, -y) , \quad B^a_{\mu}(x, y) = B^a_{\mu}(x, -y) . \]
(6)
The effective 4D Lagrangian and the Feynman rules for the interactions of KK excitations has been discussed in [11]. The tree level masses of the particles in the SM fields’ towers are multiples of \( M = 1/R \). The interactions of the KK excitations are similar to those of the SM partners; with the obvious caveat that in the case of electroweak interactions, the fermion fields in the left handed doublet \( Q_L \) couple to the electroweak gauge fields as pure \( SU(2)_L \) doublets, while the \( Q_R \) fermion fields couple only to the hypercharge \( U(1)_Y \) gauge field. Moreover, the interactions between matter fields obey KK number conservation rules (at tree level), which requires that KK particles be produced in pairs at colliers (see for example [14, 11]).

The interactions between matter and gravity are obtained from the following 4 + \( N \) dimensional action:
\[ S_{\text{int}} = -\frac{\kappa}{2} \int d^{4+N}x \delta(x^6) \ldots \delta(x^N) \hat{h}^{\mu \nu} T_{\mu \nu} \]
(7)
with \( T_{\mu \nu} \) the energy-momentum tensor of the 5D matter and \( \kappa \) the strength of the 4 + \( N \) gravitational coupling (related to the 4D one by \( \kappa = \hat{\kappa} V^{-1/2}_N \)). To obtain the effective 4D Lagrangian, one needs to expand the fields in (7) in KK modes and integrate over the extra dimensions (which essentially means the fifth dimension, due to the delta functions).
More details can be found in [16]. The Lagrangian and resulting Feynman rules for matter-gravitation interactions are similar to those obtained in [13] for the case of matter propagating into four dimensions; one has extra couplings to the vector and scalar gravitons due to components of the matter energy-momentum tensor involving the fifth dimension:

\[ L_{\text{int}} = -\frac{\kappa}{2} \sum_n \left\{ \left[ \tilde{h}^{\bar{n}}_{\mu\nu} + \omega \left( \eta_{\mu\nu} + \frac{\partial_{\mu} \partial_{\nu}}{m_{\tilde{n}}^2} \tilde{\phi}^{\bar{n}} \right) \right] T_{\bar{n}5}^{\mu\nu} - 2\tilde{A}^{\bar{n}}_{\mu5} T_{n5}^{\mu} + \left( \sqrt{2} \tilde{\phi}_{55}^{\bar{n}} - \xi \tilde{\phi}^{\bar{n}} \right) T_{n5}^{n5} \right\}, \quad (8) \]

with \( \omega = \sqrt{2/3(N+2)} \). Moreover, the interaction vertices are multiplied by form-factors

\[ F^{(c,s)}_{(l,m|n)} \sim \frac{1}{\pi R} \int_0^{\pi R} dy \left( \cos, \sin \right) \left( \frac{ly}{R} \right) \left( \cos, \sin \right) \left( \frac{my}{R} \right) \exp \left( 2\pi i \frac{nx}{r} \right) \quad (9) \]

(here \( l \) and \( m \) are the KK numbers of the matter excitations, while \( n = n_5 \) is the fifth component of the graviton KK number \( \tilde{n} \)), which describe the overlap of the graviton and matter wave functions in the fifth dimension. As we shall see in the following, these form-factors play an important role in the production of KK excitations of matter.

The phenomenology of the UED model on the fat brane is significantly affected by the inclusion of the gravitational interactions. In absence of gravity, KK number conservation at tree level [4] implies that the first level KK excitations are stable (since they are also degenerate in mass). Radiative corrections [5] will break the degeneracy, and introduce boundary terms violating KK number conservation; however, KK parity is still conserved, and the lightest KK particle (LKP) is stable. The phenomenology of such a model [6] results from the pair production of KK excitations of quarks and gluons in hadron colliders, which will then decay to LKP (which is the photon excitation \( \gamma^* \)) radiating neutrinos, leptons and/or quarks. The LKP, being weakly interacting and stable, will appear as missing energy in the detector. The observable jets or leptons have an upper limit on their energy given by the split between the KK masses of the initial quark or gluon excitations and the \( \gamma^* \), therefore, they can be hard to see. The resulting signal is at first glance similar to that of a supersymmetric model with almost degenerate superpartner masses, where the lightest supersymmetric particle is a neutralino.

Introducing gravitational interactions affects the phenomenology in the following way. First it can modify the decay pattern of KK excitations: KK quarks and gluons produced at a hadron collider can decay directly to SM quarks and gluons plus gravitons. The signal in this case will be two jets plus missing energy (associated with the graviton) [11]. Depending on the relative magnitudes of the gravitational decay widths compared to the decay widths between first level KK excitations of matter, it is also possible that the KK quarks and gluons will first decay to the LKP, which then will decay gravitationally; the signal in this case will be two high \( p_T \) photons plus missing energy (and several soft jets and/or leptons from the primary decays of the \( q^*, g^* \)) [10]. Second, one can now have production of a single KK excitation of matter, mediated by gravity. The case when the gravitons involved in production are virtual particles has been discussed in [12]; in this article we will discuss the case when gravitons appear as final state particles.
Figure 1: Feynman diagrams contributing to the production of a $g^*$ and a graviton KK excitation (either $h_{\mu\nu}, A_{\mu i}$ or $\Phi_{ij}$) at hadron colliders.

3 Processes with final state gravitons

In this section we will discuss some characteristic features of hadron collider production of KK gravitons and either Standard Model particles or their KK excitations. A typical set of Feynman diagrams contributing to these processes is shown in Fig. 1; these correspond to the case of a final state gluon excitation and a KK graviton. Similar diagrams contribute for the SM gluon production, but only with the spin 2 gravitons $h_{\mu\nu}$ in the final state (since the SM particles do not couple to the vector gravitons, and their coupling to the scalar gravitons is proportional to their mass, and therefore quite small).

Let us first discuss the production of SM matter particles in the final state. The amplitudes then are similar to those evaluated in the pure ADD case \cite{17,18} (when matter lives on the 4D brane), with the only difference being the appearance of the thick brane form-factor

$$\sigma = |\mathcal{F}_{00|n_5}|^2 \sigma_{ADD},$$

(10)

with \cite{16}:

$$\mathcal{F}_{00|n_5} = \frac{1}{\pi R} \int_0^{\pi R} dy \exp \left( \frac{2\pi i n_5 y}{r} \right) = i \frac{e^{ix} - 1}{x}. \quad (11)$$

In the above expression, we have defined $x$ as $x = \pi m_5 R$, where $m_5 = 2\pi n_5/r$ is the graviton momentum along the fifth dimension. Note that the absolute value of the form-factor is smaller than one, so its contribution has the effect of multiplying the total cross-section (obtained after adding the contributions of all the gravitons in the KK tower) by a parameter $r < 1$. However, this is not a big effect. By numerical simulations, we find that the parameter $r$ takes values roughly in the interval 1 (corresponding to the case $1/R \gg M_S$, \cite{19}).
where $M_S$ is the upper limit on the graviton mass contributing to the process\(^4\) to around 0.7 (corresponding to the case when $1/R$ is of the same order of magnitude as $M_S$).

At first glance this might appear counterintuitive. Indeed, we know that for more than two extra dimensions, generally heavy gravitons will bring the dominant contribution to the total cross-section

$$\sigma^T = \sum_{\vec{n}} \sigma^{\vec{n}} = \frac{M_{Pl}^2}{M_D^{N+2}} \int m_h^{N-1} dm_h \, d\Omega_N \, \sigma^{\vec{n}}$$

(12)

(where we have replaced the sum over graviton states by an integral \([13]\)), due principally to the fact that the density of graviton states increases as $m_h^{N-1}$. At large masses, the form-factor \([11]\) behaves like $1/m_5^5$, therefore one should expect to get substantial reduction in the total cross-section. However, while it is true that most of the cross-section comes from large values for $m_h = 2\pi\sqrt{n^2}/r$, that is for $m_h$ of order $M_s$, this actually corresponds to significantly smaller values\(^5\) of $m_5 = 2\pi n_5/r$. As a consequence, most of the gravitons contributing to the total cross section have $x = \pi m_5 R \ll 1$, and therefore $|F^{00}_{\vec{n}|n_5}|^2 \sim 1$.

Let us consider next the production of gravitons together with the KK excitation of a quark or gluon in the final state. Let us for now assume that the $q^*$ or $g^*$ will decay to a Standard Model quark or gluon by radiating a graviton. Then, the phenomenological signal will be a jet plus missing energy (carried away by the two gravitons in the final state). So at first order the signal is indistinguishable from that coming from the production of a SM quark or gluon and a graviton. Moreover, since in this case we have to produce also a massive particle in the final state (the KK excitation of matter) one might think that this type of process will not give a significant contribution.

However, this conclusion is hasty. To see that, let us consider again the cross-section for the production of a SM particle with a graviton of mass $m_h$. From dimensional analysis (see also \([18]\)), one can estimate this cross-section to be of order

$$\sigma_{SM} \sim \frac{\alpha_s}{M_{Pl}^2} \left(1 + \mathcal{O}\left(\frac{m_h^2}{s}\right)\right).$$

(13)

(assuming here $m_h^2 \ll s$) Let us consider the case of a KK matter particle of mass $M$ in the final state. A naive estimate will give an expression of the form \([13]\), with terms of order $M^2/s$ in the final state. However, if one evaluate the amplitude squared for the process with the spin 2 graviton in the final state, one obtains

$$\sigma_{KK} \sim \frac{\alpha_s}{M_{Pl}^2} \left(\frac{M}{m_h}\right)^4 \left(1 + \mathcal{O}\left(\frac{m_h^2}{s}\right) + \mathcal{O}\left(\frac{M^2}{s}\right) + \ldots\right).$$

(14)

The term $(M/m_h)^4$ can lead to a great enhancement of the cross-section for producing light gravitons in the final state. To see how big this enhancement is, one just need remember that $m_h$ can be as low as eV, while $M$ is of order TeV; this leads to a $10^{48}$ factor. The

\(^4\)While theoretically all gravitons in the KK tower can contribute to the process, there is an upper limit on the graviton mass imposed by the collider energy and luminosity considerations.

\(^5\)For example, if we assume a flat distribution for the cross-section over a sphere of radius $M_S$ in $N$ dimensions, the average value for $m_5$ would be of order $M_S/N^2$. 

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appearance of this enhancement factor is due to the breaking of translation invariance in the 5th dimension by the brane. This has as consequence the non conservation of 4D energy-momentum tensor of the matter $k^\mu T_{\mu\nu} \neq 0$, for interactions involving matter excitations with different KK numbers. Instead, one has $k^M T_{MN} = 0$ (with the indices $M, N$ going from 0 to 5), or

$$k^\mu T_{\mu\nu} = -k^5 T_{5\nu} \sim \Delta m_{kk},$$

where we used the fact that the momentum in the fifth dimension is proportional to the KK mass. In our case, we have one SM particle becoming a first level excitation, therefore $\Delta m_{KK} = 1/R = M$. Then, if one considers the amplitude for the creation of a KK matter excitation by the radiation of a graviton with momentum $k$:

$$\sum_{\text{spin}} |\mathcal{M}(q \rightarrow q'h^\alpha)|^2 \sim \langle q^* | T_{\mu\nu} | q \rangle \langle q^* | T_{\rho\sigma} | q \rangle B^{\mu\nu,\rho\sigma}(k),$$

one sees that due to terms $\sim k^\mu k^\nu k^\rho k^\sigma/m_h^4$ in the graviton polarization sum $B^{\mu\nu,\rho\sigma}(k)$ (see, for example, [13] for the full expression), one will obtain $\sum_{\text{spin}} |\mathcal{M}(q \rightarrow q'h^\alpha)|^2 \sim (M/m_h)^4$. Similar behavior holds for the production of a scalar graviton in the final state (although in this case terms $\sim k^\mu k^\nu/m_h^2$ are due to the $\partial^\mu \partial^\nu/m_h^2$ factor in the interaction lagrangian [13] rather than to the sum over polarizations), while for the case with a vector graviton field $A^\mu$ in the final state, one has $\sigma \sim \alpha_s/M^2 (M/m_h)^2$.

A behavior of the production cross-section $\sim (M/m_h)^4$ would mean that for the case of $N = 2, 3$ one would be able to probe very large values of $M_D$ (by contrast, the total production cross section for large $N$ values is not affected very much, since, as we have mentioned above, the contributions of heavy gravitons are enhanced by a density of states factor $m_h^{N-1}$, which will win over $(1/m_h)^4$ factor). However, we still have to take into account the form factors describing the overlap of graviton and matter wave functions on the brane. For the processes with the spin-2 graviton or the scalar gravitons in the final state, the form factor multiplying the production cross-section will be $|\mathcal{F}_{01|n_5}^c|^2$, while for the vector graviton is $|\mathcal{F}_{01|n_5}^s|^2$. Here

$$\mathcal{F}_{01|n_5}^{c(s)} = \sqrt{2} \pi R \int_0^{\pi R} dy (\cos, \sin)(y/R) \exp\left(2\pi i n_5 y R\right) ,$$

and therefore

$$|\mathcal{F}_{01|n_5}^c|^2 = \frac{4x^2}{(\pi^2 - x^2)^2} \left[1 + \cos(x)\right], \quad |\mathcal{F}_{01|n_5}^s|^2 = \frac{\pi^2 |\mathcal{F}_{01|n_5}^c|^2}{x^2} ,$$

with $x$ as defined after Eq. (11). According to the discussion above, generally small values of $x$ are relevant for the total cross-section; we then have

$$|\mathcal{F}_{01|n_5}^c|^2 \sim \frac{8x^2}{\pi^2} = \frac{8 m_5^2}{M^2} , \quad |\mathcal{F}_{01|n_5}^s|^2 \sim \frac{8}{\pi^2} , \quad \text{for } x \ll 1 .$$

We see then that the form-factors contribute additional terms of order $(m_h/M)^2$ to the cross-section for the production of spin-2 and scalar gravitons. For a small number of extra
dimensions ($N = 2, 3$) this has an effect of making the enhancement factor in front of the cross-section the same for all final states, roughly $(M/m_h)^2$. This will enhance the cross-section somewhat, but not very much. (If one takes into account the density of graviton states $m_h dm_h$ for $N = 2$, one sees that this is a roughly logarithmic effect). In fact, we find that the cross-section for production of gravitons with a KK excitation is still smaller than the production of gravitons with SM particles (although typically lighter gravitons are predominant in the first case). For $N = 4$ to 6, the form factor has a net effect of reducing the contributions coming from spin 2 and scalar gravitons in the final state (unlike the enhancement due to breaking of 5D translational invariance, which is important mostly for light gravitons, the form-factor cancellation effect is valid for large graviton masses as well). As a consequence, we find that for such processes, the gravitons appearing in the final state for values of $N$ larger than 4 are mostly vector gravitons. By contrast, for $N = 2, 3$ generally final states with spin-2 gravitons will dominate.

4 Results

In this section we present results for phenomenological signals at Tevatron Run II and LHC due to the production of an SM particle and/or a KK excitation together with a KK graviton in the final state.

We start by considering the monojet plus missing energy signal. There are two contributions to this signal: first comes from the production of a SM quark or gluon in the final state. The second contribution comes from the production of a KK excitation of a quark and gluon, which subsequently will decay by radiating a graviton to a SM particle. As mentioned in the previous section, the first type of contribution is generally dominant. The signal is then roughly the same one would obtain in a pure ADD theory (with matter stuck on a 4D brane). There is a small difference for our model due to the appearance of the form factor associated with matter propagating in the 5th dimension; however, the numerical importance of the form factor is small.

In Fig. 2 we present the jet + $\not{E}_T$ cross section as a function of the fundamental gravity scale $M_D$ for Tevatron Run II and LHC. Cuts on the jet transverse momentum ($p_T > 200$ GeV at Tevatron, $p_T > 1$ TeV at LHC) and rapidity ($|y| < 3.0$) have been used. We estimate the SM background (assumed to come only from physics, jet + $Z$ production, with $Z$ decaying to neutrinos) at parton level, using MADEVENT [19], and with these cuts we obtain around 0.14 pb for Tevatron and 10 fb for LHC. The results are similar with the pure ADD cross-sections presented in [18, 17], but for a numerical comparison one should note that the definition for $M_D$ we use is slightly different (in Eq (1), a factor of $1/8\pi$ appears on the left hand side in [17], while $1/4\pi$ appears on the left hand side in [18]).

In Fig. 3 (left panel) we present the cross section for the production of one quark or gluon KK excitation and a graviton at the LHC, shown as a function of the mass of the KK particle $m_{KK}$. The same cuts as for the case of SM particle production are used; we have used a value of $M_D = 5$ TeV for this plot. We see that while the production cross-section may be large enough in some cases (especially for a small number of extra dimensions) for this signal to be measurable, it is generally smaller than the signal due to production of the
SM particle together with graviton. We also note that the cross-section is somewhat flat for small values of $m_{KK}$. This behavior is due to the large $p_T$ cut imposed on the momentum of the observable jet. Since in this case the jet comes from the decay of a massive particle (the KK excitation), its transverse momentum will tend to increase with the mass of the particle. This partially compensates for the decrease in cross-section due to the production of heavier particles.

In Fig. 3 (right panel) we present the cross section as a function of the cut $p_T^{min}$ on the transverse momentum for the observable jet. The solid line corresponds to the case of SM particle production, while the dashed and dotted line correspond to the case of gluon/quark KK excitations in the final state. (with $m_{KK} = 2$ TeV for the dashed line and $m_{KK} = 3$ TeV for the dotted line). The plot is made for $N = 2$ extra dimensions, with $M_D = 5$ TeV. As noted above, for small values of $p_T^{min}$, the cross-section for the production of the SM particles dominates (this is a consequence of the form-factor $F_{01|a}^c$ multiplying the amplitude rather than the appearance of a massive KK particle in the final state). However, the transverse momentum of the jets due to production of a SM particle falls faster than the $p_T$ of the jets coming from the decay of the heavy KK excitation, and as it can be seen in figure, at very large $p_T$ the two signals are of comparable magnitude. This suggests that if one wants to look for the production of KK excitations of matter in this channel, one should look primarily at very high $p_T$ events.

However, a better possibility of identifying KK particle production at hadron colliders will appear if these excitations decay first to the LKP ($\gamma^*$), which in turn decays gravitationally. The signal in this case will be a high $p_T$ photon in the final state plus missing energy (there will also be some soft jets and leptons, but we will not consider those in our analysis). The SM background in this case is much smaller that for the case of a jet + $/E_T$; the
Figure 3: Left panel: the jet+ missing energy cross section from graviton and KK quark or gluon production at LHC. The solid line corresponds to $N = 2$, while the dashed line corresponds to $N = 4$. Right panel: the distribution of the cross-section as a function of the cut imposed on the jet transverse momentum, for production of SM particle (solid line), and production of KK excitations with $m_{KK} = 2\text{ TeV}$ (dashed line) and $m_{KK} = 3\text{ TeV}$ (dotted line).

Signal due to the production of a SM photon with a graviton will also be smaller, since the production process for such a signal will be an electroweak process rather than a strong one. For example, at the LHC, for a $p_T$ cut of 500 GeV, the SM background is $\sim 1\text{ fb}$. With a 100 fb$^{-1}$ of integrated luminosity, a $5\sigma$ discovery would then require 50 signal events, or a cross-section of 0.5 fb. From direct production of a SM photon with a graviton, the values of $M_D$ for which the cross-section will reach 0.5 fb will be 5.4 TeV for $N = 6$, 6 TeV for $N = 4$ and 8.3 TeV for $N = 2$.

In the case of production of a gluon/quark KK excitation which subsequently decays to a photon, the values of $M_D$ corresponding to a 0.5 fb cross-section can be as high as $\sim 7$ TeV for $N = 6$, 10 TeV for $N = 4$ and 40 TeV for $N = 2$, depending on the value of $1/R$. We show in Figs. 4 [5] (left panel) with the solid lines the discovery reach in the $(M_D, 1/R)$ plane (that is, for points below and to the left of the solid lines, the cross-section will be bigger than 0.5 fb). The dashed lines correspond to values of parameters for which the gravitational decay widths start becoming important; that is, for points below the dashed lines the quark and gluon KK excitations will decay predominantly to $\gamma^*$, while for points above they will decay directly to SM quarks and gluons through graviton radiation. Therefore, in the region below both the solid and dashed lines, the signal will be photon + $E_T$, and it will be large enough to ensure discovery. We see that in this channel we can probe values of $M_D$ similar to those achievable in the jet + $E_T$ channel for $N = 4$ and $N = 6$ (from Fig. 2) and almost twice as large for $N = 2$ (the $5\sigma$ discovery reach from jet + missing energy being $\sim 20$ TeV in this case).
The case for the Tevatron is somewhat different. As it can be seen from Figs. 4, 5, the requirement that $g^*$ and $q^*$ decay first to the LKP implies rather large values of $M_D$ (> 10 TeV for $N = 2$). This means that the production cross-section is highly suppressed.

![Figure 4](image1.png)

**Figure 4:** Solid lines: the 5σ discovery reach at the LHC in the photon + $E_T$ channel for $N = 2$ (left panel) and $N = 4$ (right panel). For values of $M_D, 1/R$ below the dashed lines, the KK quarks and gluons decay first to the LKP.

![Figure 5](image2.png)

**Figure 5:** Left panel: the 5σ discovery reach at the LHC in the photon + $E_T$ channel for $N = 6$. Right panel: the SM photon + $E_T$ cross-section at the Tevatron Run II, with $p_T > 100$ GeV (solid, dashed and dotted lines correspond to $n = 2, 4$ and 6 extra dimensions respectively).
Typically, for $N = 4, 6$ there is just a small region of values for $M_D$ where $g^*$ and $q^*$ both decay to $\gamma^*$ and are produced in enough numbers to be observable. However, in that region the signal coming from production of SM photons plus KK gravitons is predominant. We show in Fig. 5 (right panel) the cross-section for SM photon production plus $E_T$ (from KK gravitons), with a cut on photon $p_T$ of 100 GeV. The Standard Model background (from $Z\gamma$ production) is $\sim 80$ fb. It is interesting to note that the the $M_D$ discovery reach at the Tevatron is roughly similar in the jet + $E_T$ channel versus photon + $E_T$ channel. The reason is that while the production cross-section is suppressed by a factor $\alpha_{em}/\alpha_s \sim 1/10$, the background is similarly suppressed, and one can use softer cuts (using a $p_T$ cut of 100 GeV as opposed to 200 GeV will increase the cross-section by a factor of 10). Moreover, the predominant initial state responsible for the production cross-section is $q\bar{q}$, which favors processes with photons in the final state (whereas for the LHC is $qg$ and $gg$, resulting in additional suppression of final state photons).

5 Conclusions

The scenario of a universe with more than four dimensions leads to interesting and testable experimental consequences. In this paper we studied a particular class of models, where the matter fields propagate on a 4+1 dimensional fat brane embedded in a 4+$N$ higher dimensional space. Gravity propagates in the whole bulk, with dimensions of order inverse eV, which helps solve the hierarchy problem, while the thickness of the brane on which matter propagates is of order inverse TeV.

The standard phenomenology associated with UED models is affected by the inclusion of the gravitational interactions. These break KK number conservation, and therefore allow the decays of the KK excitations of matter, as well as single production of KK excitations. In this paper we consider signals with final states containing a KK graviton. These can be produced together with a SM quark or gluon (as in the ADD case, when matter is restricted to the 4D brane), as well as together with the KK excitations of such particles. The phenomenological signal in the latter case depends on the decay of the $q^*/g^*$ excitation, and can be either be a jet with missing energy (if gravitational decays dominates), or photon plus missing energy (if the $q^*/g^*$ decays first to the $\gamma^*$).

We find that, for final states consisting of a monojet plus missing energy, the production cross-section for SM particle plus a graviton (similar to that obtained in pure ADD models) is typically larger than the one for KK particle plus graviton. However, for the case of $N = 2$ extra dimensions, in regions with large transverse momentum the signal associated with the production of a KK excitation is comparable in magnitude to the signal resulting from the production of a SM particle. In our model, using this channel one can then probe the fundamental scale of gravity $M_D$ starting from 1.5 TeV up to 3 TeV at the Tevatron, and starting from 8 TeV up to 25 TeV at the LHC (the lower values correspond to $N = 6$, while the higher values correspond to $N = 2$ extra dimensions).

Things are somewhat different for the high $p_T$ photon plus missing energy channel. The cross-section due to SM photon production is reduced due to the appearance of the electroweak coupling constant, as well as due to the requirement that the initial state is $q\bar{q}$.
(which affects mostly the LHC case). One then finds at the LHC, for sufficiently small values for the mass of matter KK excitations $M$ (such that these decay first to the LKP $\gamma^*$), the signal associated with production of KK matter dominates. One can probe values of $M_D$ starting from 7 TeV (for $N = 6$) up to 40 TeV (for $N = 2$). The larger reach in the $N = 2$ case compared to the jet + $\not{E}_T$ final state is due to lower background in the photon channel, as well as to the enhancement of the production cross-section for light gravitons in the final state. On the other hand, for values of $M_D$ accessible at Tevatron, the quark and gluon excitations will decay mostly to gravitons plus jets, and the dominant source of final state photons will be due to the production of the SM particles. Again, due to smaller backgrounds, the discovery reach for $M_D$ in this channel is comparable to the one obtained in the jet + $\not{E}_T$ channel.

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