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(Gravity and) Collider Signals for Universal Extra Dimensions

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Overview

Model description - UED

- particle content
- interactions

Production of KK excitations at hadron colliders

One loop corrections

Decays of KK excitations and collider signals

- SM decays and stable LKP

Gravity - matter interactions

- decays mediated mainly by gravity:

  the two jets signal

- decays mediated mainly by SM interactions:

  the two photons signal

- mixed case

Timeline

The UED scenario:

- first studied by Appelquist, Cheng and Dobrescu (2001) implications for precision electroweak data.
- Rizzo (2001): lepton and hadron collider phenomenology
- Cheng, Matchev and Schmaltz (2002): model at one loop

Model Description

• Particle Content

all SM particles propagating in one extra dimension of radius $R \sim 1\ \mathrm{TeV}^{-1}$

flat

Expansion in KK modes:

for gauge fields (similarly for the Higgs field)

$$A^\mu(x,y) = \frac{1}{\sqrt{\pi R}}\left[\underbrace{A_0^\mu(x)}_{\text{SM}} + \sqrt{2}\sum_{n=1}^{\infty} \underbrace{A_n^\mu(x)}_{\text{KK excitations}} \cos\left(\frac{ny}{R}\right)\right]$$

for fermionic fields

need for chiral fermions $\Rightarrow$ impose an orbifold structure on the fifth dimension: S_1/Z_2, with two sets of fields:

SU(2) doublet: left-hand fields even and right-hand fields odd under the Z_2 parity

$\longrightarrow$ $y \in [0, \pi R]$

$$Q(x,y) = \frac{1}{\sqrt{\pi R}}\left\{Q_L + \sqrt{2}\sum_{n=1}^{\infty}\left[Q_L^n \cos\left(\frac{ny}{R}\right) + Q_R^n \sin\left(\frac{ny}{R}\right)\right]\right\}$$

SU(2) singlet: left-hand fields odd and right-hand fields even under the Z_2 parity

$$q(x,y) = \frac{1}{\sqrt{\pi R}}\left\{q_R + \sqrt{2}\sum_{n=1}^{\infty}\left[q_R^n \cos\left(\frac{ny}{R}\right) + q_L^n \sin\left(\frac{ny}{R}\right)\right]\right\}$$

the SM field : $q = Q_L + q_R$

KK excitations:

$$\underline{q_n^\bullet = Q_L^n + Q_R^n} \qquad \underline{q_n^\circ = q_L^n + q_R^n}$$

- **Interactions**

the effective 4D Lagrangian:

$$\mathcal{L}_4(x) = \int_0^{\pi R} dy\, \mathcal{L}(x,y)$$

Mass of the n-th KK excitation:

$$m_n = \sqrt{\left(\frac{n}{R}\right)^2 + m_{SM}^2}$$

for light quarks and leptons: $m_n \simeq n/R$ → same level degeneracy

KK excitations interaction:

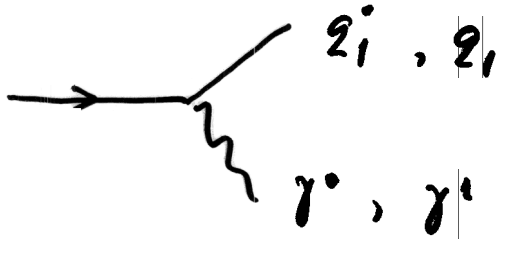
$$\mathcal{L}_4(\psi_n A_k \psi_m) \sim \bar{\psi}_n \gamma_\mu \psi_n A_k^\mu \times \left[\int_0^{\pi R} \cos(\frac{ny}{R}) \cos(\frac{my}{R}) \cos(\frac{ky}{R})\, dy\right]$$

⇒ KK number conservation rules :

$$|m \pm n \pm k| = 0$$

⇒ pair production

⇒ no decay for first level KK excitations



but mass degeneracy

Vertex rules

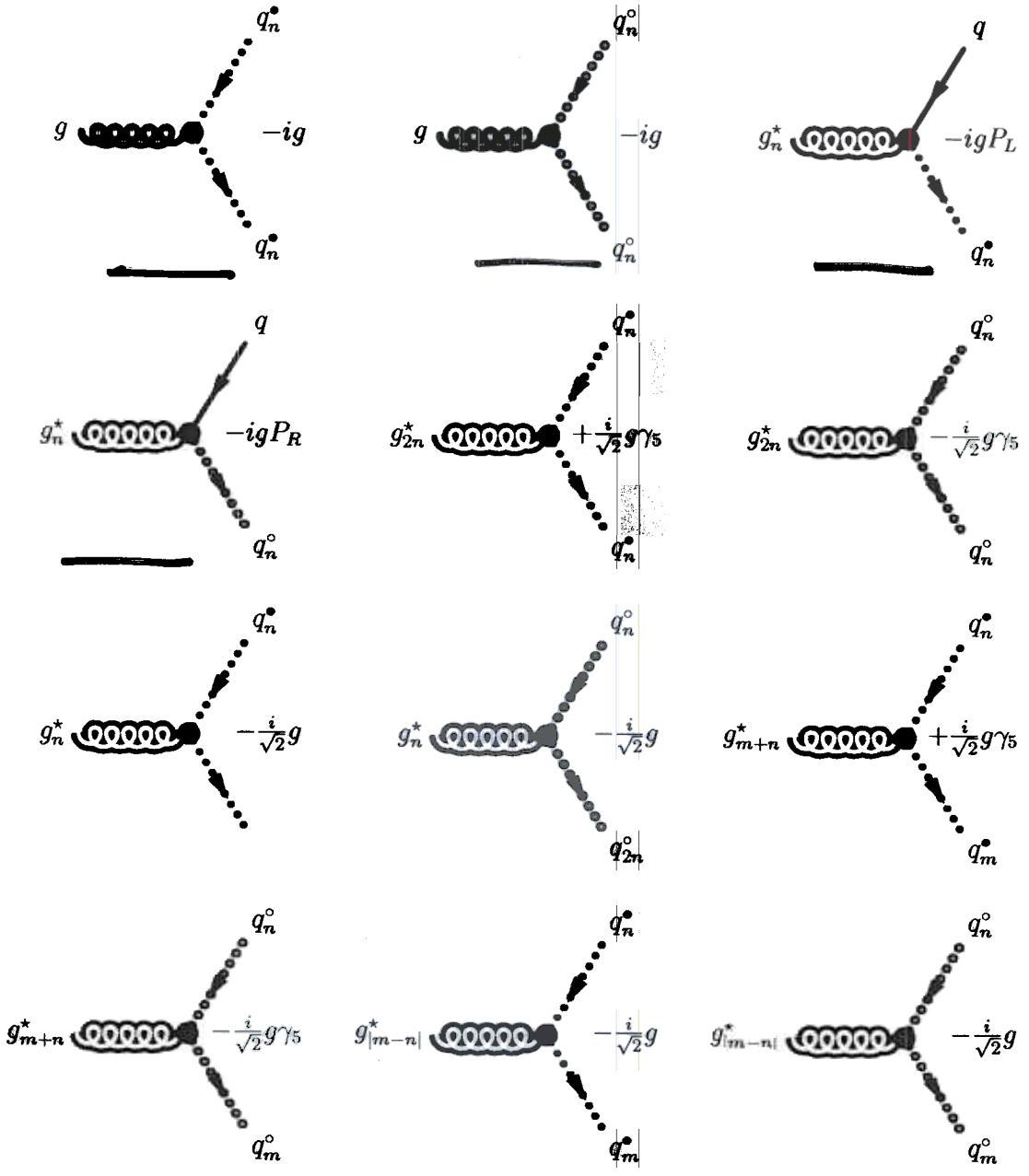


Figure 1: Relative coupling strengths of vertices involving $q^\bullet$'s and q°'s. Only the overall factors are shown.

(from Macesanu, McMullen, Nandi hep-ph/0201300)

Pair-Production rates at hadron colliders

Processes:

Double KK gluon production		KK quark-gluon production	
$gg \to g_n^\star g_n^\star$	$q\bar{q} \to g_n^\star g_n^\star$	$qg \to q_n^\bullet g_n^\star$	$qg \to q_n^\circ g_n^\star$
Double KK quark production			
$q\bar{q} \to q_n^\bullet \bar{q}_n^\bullet$	$q\bar{q} \to q_n^\circ \bar{q}_n^\circ$	$gg \to q_n^\bullet \bar{q}_n^\bullet$	$gg \to q_n^\circ \bar{q}_n^\circ$
$q\bar{q} \to q'^\bullet_n \bar{q}'^\bullet_n$	$q\bar{q} \to q'^\circ_n \bar{q}'^\circ_n$	$qq \to q_n^\bullet q_n^\bullet$	$qq \to q_n^\circ q_n^\circ$
$q\bar{q}' \to q_n^\bullet \bar{q}'^\bullet_n$	$q\bar{q}' \to q_n^\circ \bar{q}'^\circ_n$	$qq' \to q_n^\bullet q'^\bullet_n$	$qq' \to q_n^\circ q'^\circ_n$
$q\bar{q} \to q_n^\bullet \bar{q}_n^\circ$	$q\bar{q} \to q_n^\circ \bar{q}_n^\bullet$	$qq' \to q_n^\bullet q'^\circ_n$	$qq' \to q_n^\circ q'^\bullet_n$
$q\bar{q}' \to q_n^\bullet \bar{q}'^\circ_n$	$q\bar{q}' \to q_n^\circ \bar{q}'^\bullet_n$	$qq \to q_n^\bullet q_n^\circ$	

Figure 2: Subprocesses leading to double KK production at hadronic colliders. Not shown are subprocesses that are simply related by the exchange of a particle and antiparticle.

Collider reach (100 events):

Tevatron Run I : $1/R = 350$ GeV

Run II : 480 (with 2fb^{-1}) to 540 GeV (with 15fb^{-1})

LHC : 3 TeV, with 100 fb^{-1} of luminosity.

total

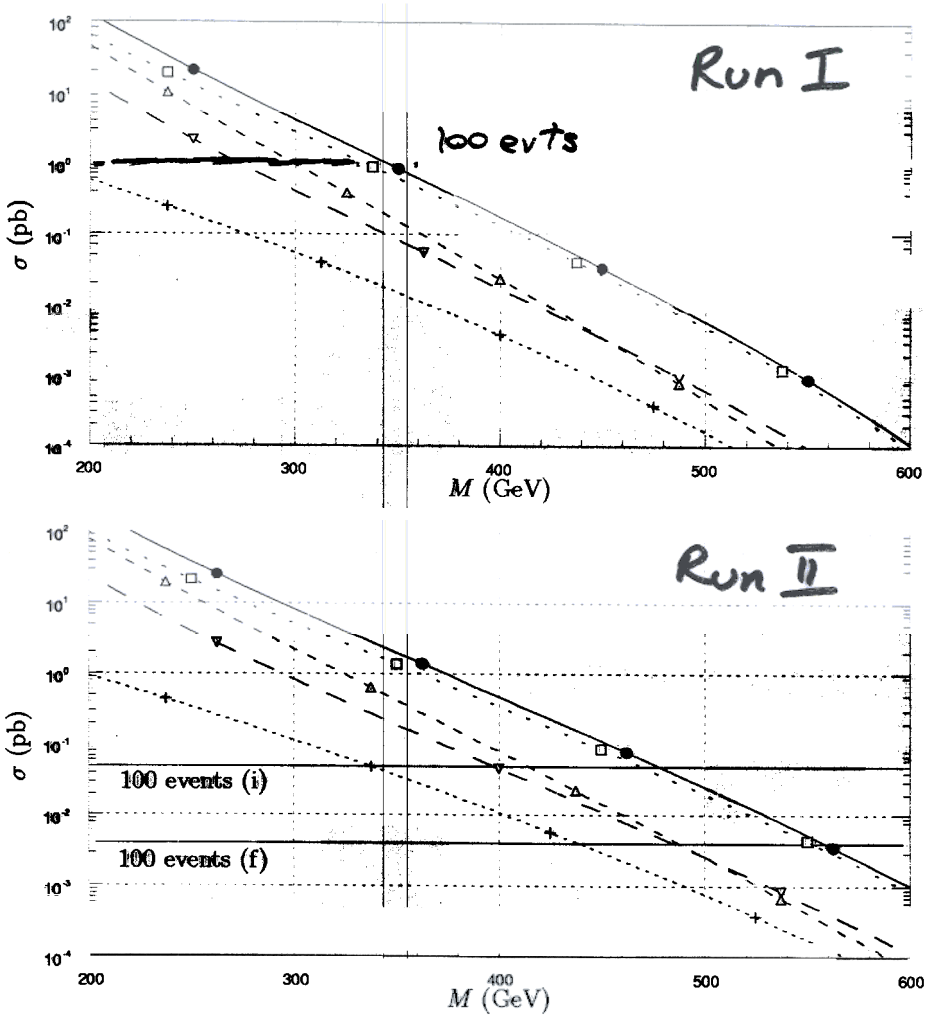
quark pair

quark - gluon

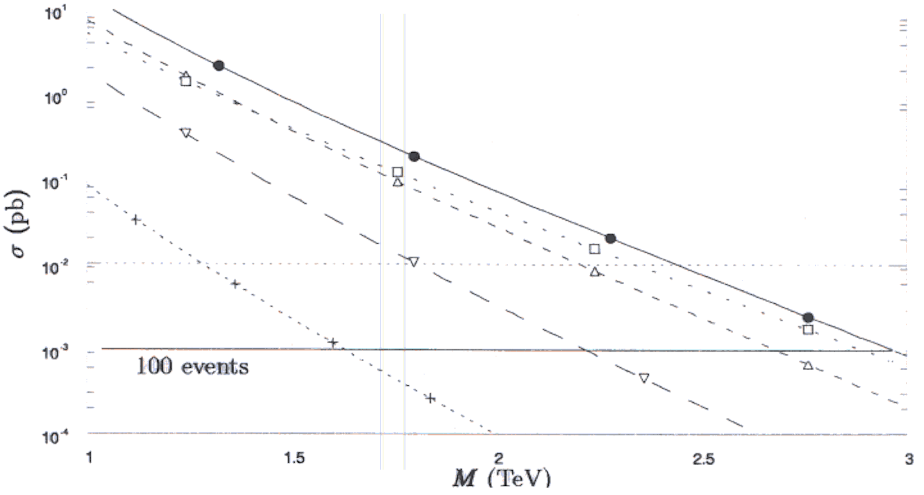
gluon - gluon

$t^* \bar{t}^*$

Tevatron



LHC



One loop theory

(Cheng, Matchev and Schmaltz: hep-ph/0204342)

• on $M4 \times S_1$ space, we get mass corrections due to virtual particles propagating in bulk:

$$\delta\left(m_{g_n}^2\right) = -\frac{3}{2}\frac{g_s^2}{16\pi^4}\zeta(3)\left(\frac{1}{R}\right)^2 \ , \ \delta(m_{f_n}) = 0$$

these bulk corrections are finite, and the same for each KK level.

• on an orbifold ($M4 \times S_1/Z_2$), the breaking of translational invariance at the orbifold boundaries generates localized corrections to the lagrangian (Georgi, Grant and Hailu). But,

Upon renormalization, the finite part remains undetermined $\Rightarrow$ need an *ansatz* to specify them.

Assuming (1) that they vanish as some cutoff scale Λ and
(2) universality, we have:

boundary corrections to the massess of KK excitations:

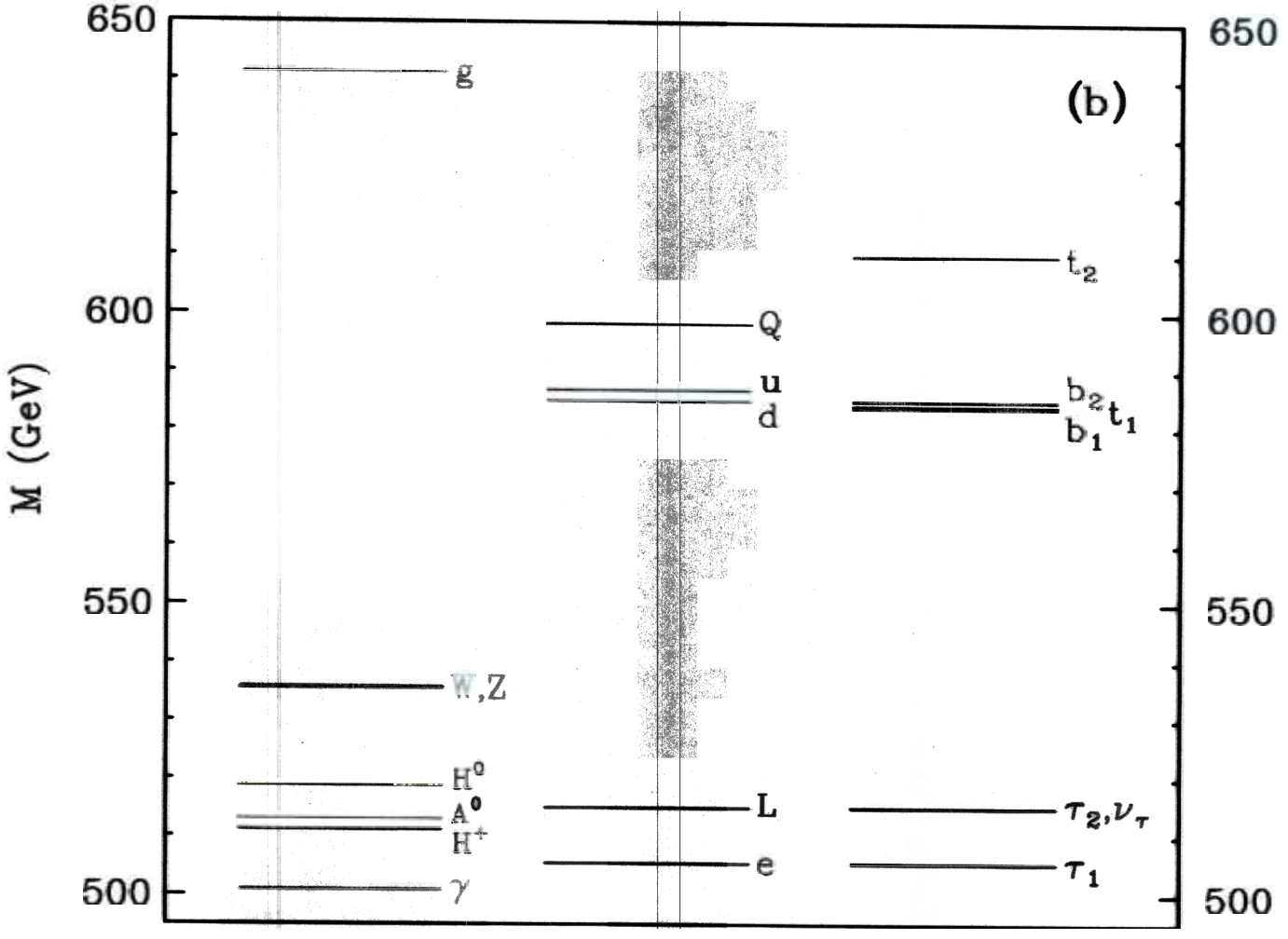
$$\delta_b(m_{g_n}^2) = m_n^2\,\frac{23}{2}\,\frac{g_s^2}{16\pi^2}\ln\frac{\Lambda^2}{m_n^2}$$

$$\delta_b(m_{f_n}) = m_n\,\frac{g_s^2}{16\pi^2}\ln\frac{\Lambda^2}{m_n^2}$$

Note that they are of opposite sign and much larger than the bulk terms. Also these corrections increase with n.

Masses of first level KK excitations at one loop

from Cheng, Matchev and Schmaltz, hep-ph/0204...



Here $1/R = 500$ GeV, $\Lambda = 10$ TeV

Order of magnitude for one loop corrections:

- gluon excitation $\simeq 30\%$
- quark excitations $\simeq 20\%$
- lepton excitations $\simeq 5\%$

KK excitations decays and collider signals

: pair production of first level KK excitations

:a

if $\left\{ \begin{array}{l} \text{KK number conservation} \\ \text{degenerate spectrum (at tree level)} \\ \text{no other physics} \end{array} \right\} \Rightarrow$

the first level KK excitations are stable

search for long lived charged massive particles in collider experiments.

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if mass degeneracy at first level is lifted (loop corrections)

$\Rightarrow$ we will have cascade decays to the lightest KK particle (LKP) for example

$$q_1^\bullet \to q\, Z_1^* \to q\, l\, l_1^\bullet \to q\, l\, l\, \gamma^*$$

- the SM particles radiated in this decay are observable.
- γ^* (the LKP) is stable, and does not interact in the detector (it may have cosmological implications, though).

Analysis of the collider signals in this scenario have been performed by Cheng, Matchev and Schmaltz (hep-ph/0205314).

Conclusion: since the ammount of energy available to SM particles is small (being of the order of magnitude of the mass splitting between the q^* or g^* and the LKP), the signal is rather difficult to detect. (SUSY with almost degenerate spectrum)

In the $4l + \not{E}_T$ mode, the Tevatron Run II reach is about 300 GeV, while the LHC reach is about 1.5 TeV.

Gravity-mediated decays

look for new physics, which can break KK number conservation

Gravity:

in N symmetric extra dimensions, the ADD relation:

$$M_P^2 = M_D^{N+2} r^N$$

if we take M_D of order 10 TeV, then

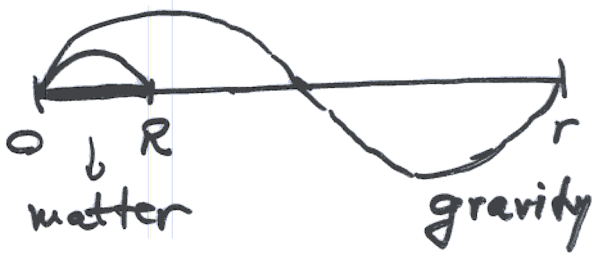
$$r \sim \text{eV}^{-1} \text{ (for } N = 2) \text{ up to keV}^{-1} \text{ (for } N = 6)$$

Consider the fat brane scenario:

- gravity propagates in $4 + N$ dimensions, with radius r
- matter can propagate along the $4D$ brane, and a limited length of order R (the thickness of the brane) along the y direction

(for models with SM fields localized on a fat brane see, for example, Georgi, Grant and Hailu, hep-ph/0007350)

we shall consider a simplified (toy) model, in which the SM fields are confined on the brane by a 'infinite well' potential (as in Rujula, Donini, Gavela, Rigolin, hep-ph/0001335)



Gravity-matter interactions

For matter in $4D$, we have:

$$\mathcal{L}_{G\psi} = \hat{h}^{\mu\nu} T_{\mu\nu} \to \sum_n \left(\tilde{h}^{\mu\nu,n} T_{\mu\nu} + \omega \tilde{\phi}^n T^\mu_\mu \right)$$

(For Feynman rules, see Han, Lykken and Zhang, hep-ph/9811350, also Giudice, Rattazi and Wells, hep-ph/9811291)

With matter in $5D$, we will have:

$$\mathcal{L}_{G\psi} = \int_0^{\pi R} \hat{h}^{MN} T_{MN} \to \sum_{l,m,n} \mathcal{F}_{lmn} \Big(\tilde{h}^{\mu\nu,n} T^{l,m}_{\mu\nu} + \omega \tilde{\phi}^n T^{\mu,l,m}_\mu + \ldots \Big)$$

The form factor $\mathcal{F}_{lmn}$ describe the superposition of the graviton wave function with the fermion wave functions along the y direction:

$$\mathcal{F}_{lmn} = \frac{\sqrt{2}}{\pi R} \int_0^{\pi R} dy \exp(i \frac{2\pi n y}{r}) \cos(\frac{ly}{R}) \cos(\frac{my}{R})$$

For the decay of the first level KK excitations:

$$|\mathcal{F}_{01n}|^2 = \frac{4}{\pi^2} \frac{x_n^2}{(1 - x_n^2)^2} [1 + \cos(\pi x_n)]$$

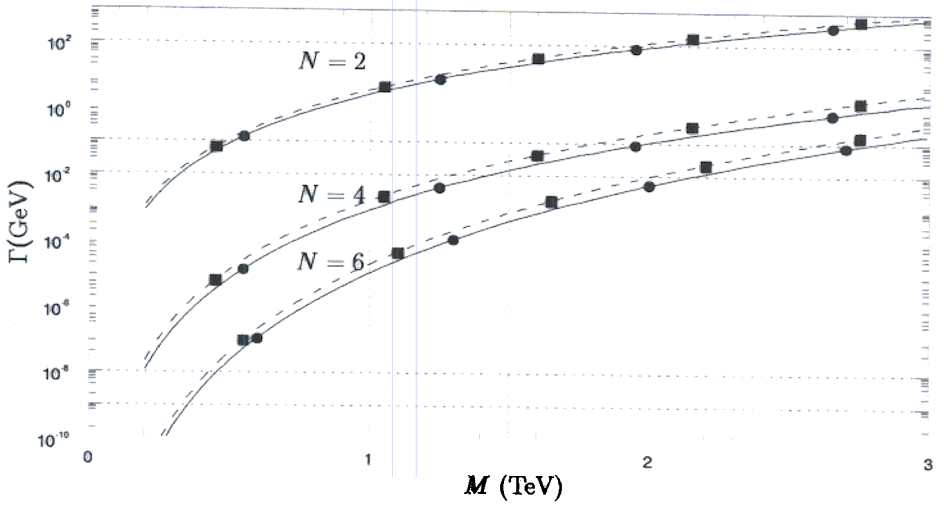
with

$$0 < x_n = \frac{2\pi n R}{r} < 1$$

$q_1 \to q_0 \, G_n$

$$\Gamma'(q^* \to q G_n) = \frac{1}{786\pi M_{pl}^2} \underbrace{\frac{M_{KK}^3}{x_n^4}}_{\text{large, for light gravitons}} \left[(1-x_n^2)^4 (2+3x_n)\right]$$

Gravity mediated decay widths



$M_D = 5$ TeV

—●— fermions

■-- bosons

Collider signals for gravity mediated decays

If the first level KK excitations are stable due to mass degeneracy (or, if the widths of the decays due to mass splitting are much smaller that the width of the decay due to gravity interactions)

$$\Gamma_{ew}, \Gamma_s \ll \Gamma_G$$

then, at a hadron collider:

$$pp \to q^* \; q^* \to q_1 G_n \; q_2 G_m$$

the signal will be two jets + missing energy ($\not{E}_T$)

Properties of the jets

- Energy : E_1, E_2 of order $M_{KK}/2$ ($M_{KK} \simeq 1/R$) - large
- transverse momentum - p_{1T}, p_{2T} also large, since the KK excitation will be produced almost at rest.
- Missing transverse energy: $\not{E}_T = |p_{1T} - p_{2T}|$ - large

Actually, these quantities depend on the mass distributions of the gravitons which mediate the decay - which is a number of extra dimensions of the space

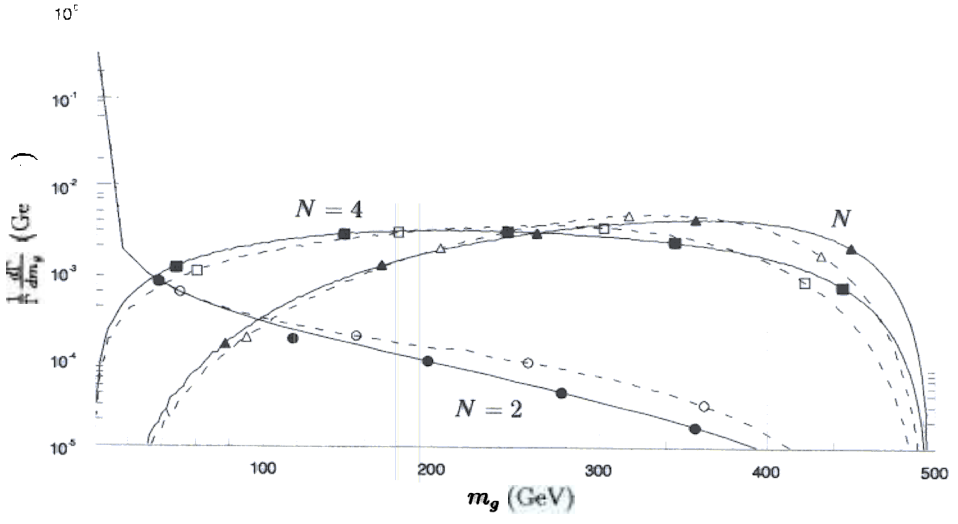
- for $N = 2$ mostly light gravitons contribute to decay: $m_G \sim$

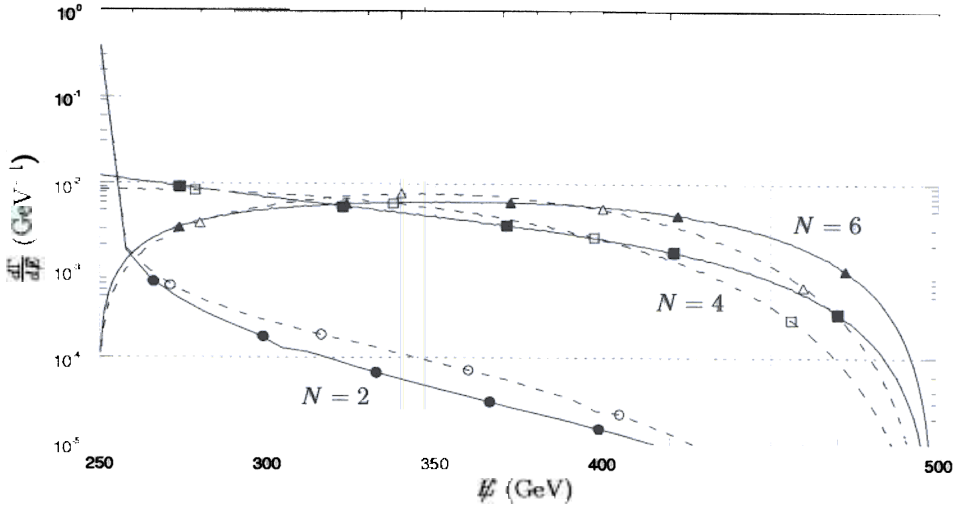
Then the jet energies have maximum value $M_{KK}/2$.

- for $N = 6$ heavy gravitons are predominant: $m_G \sim M_{KK}$

lower values for jet energies and transverse momenta.

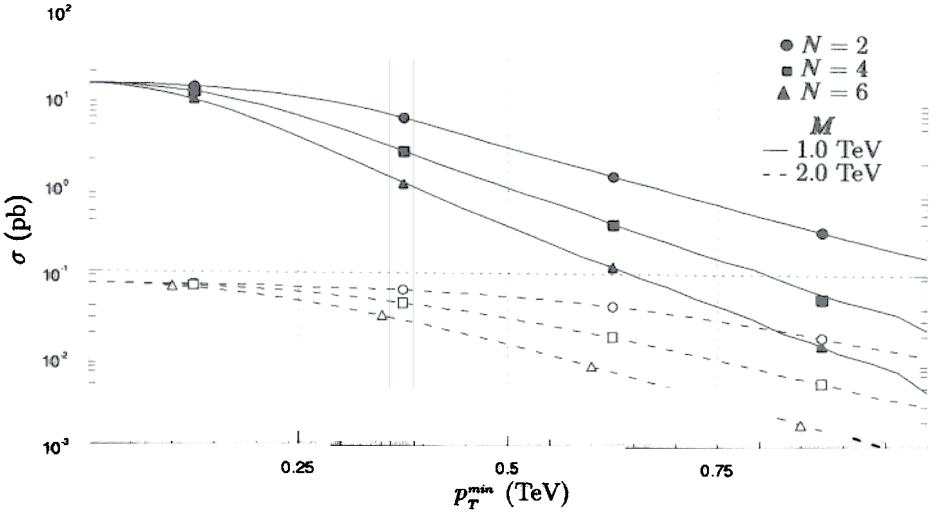
Distribution of gravitons with respect to graviton mass

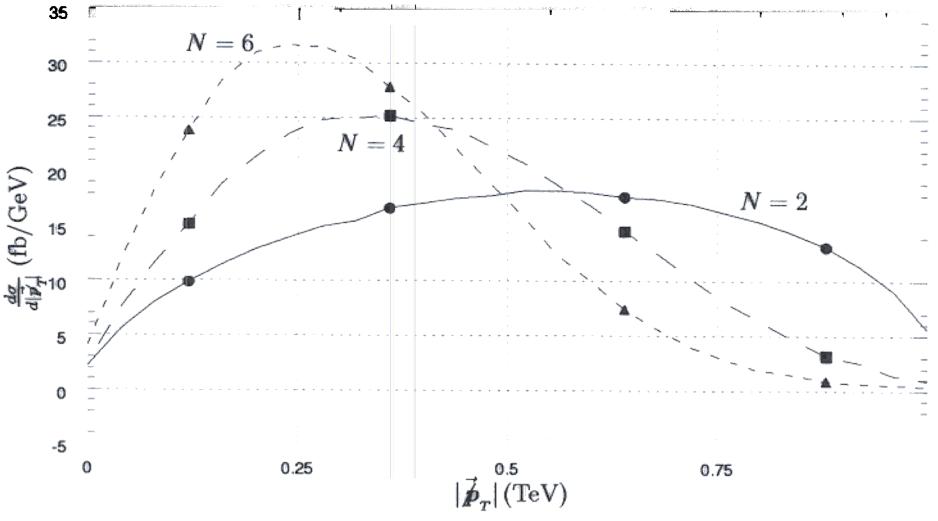




Distribution of gravitons with respect to graviton energy

Cross-section vs. p_T^{min}





Cross-section vs $\not{E}_T$

Collider reach

Backgrounds for the two jets + $\not{E}_T$ signal:

- WZ, ZZ, $q\bar{q}Z$ and $t\bar{t}$ production
- $2 \to 2$ QCD processes with mismeasurement of jet energies

Use cuts on transverse momentum and $\not{E}_T$:

p_T^{cut} (GeV)	Background (evts.)	Signal (evts.) $M = 1$ TeV $N = 2$	$M = 1$ TeV $N = 6$	$M = 2$ TeV $N = 2$	$M = 2$ TeV $N = 6$	$M = 3$ TeV $N = 2$	$M = 3$ TeV $N = 6$
100	3×10^6	1×10^6	9×10^5	7×10^3	6×10^3	84	80
200	2×10^5	9×10^5	2×10^5	6×10^3	4×10^3	80	65
300	9×10^3	4×10^5	4×10^4	5×10^3	3×10^3	73	50
400	1×10^3	1×10^5	2×10^3	4×10^3	1×10^3	65	34
500	2×10^2	5×10^4	2×10^2	3×10^3	4×10^2	58	20
600	4×10	6×10^2	3×10	2×10^3	1×10^2	50	10

Table 1: SM background and UED signals with $p_T > p_T^{cut}$, $\not{E}_T > 2p_T^{cut}$ (for 10^5pb^{-1} at LHC).

Collider reach:

Tevatron Run II : $M_{KK} = 550$ GeV

LHC : about 3 TeV

(depending on the number of extra dimensions)

Gravity in the nondegenerate mass spectrum case

Then the p ng between the masses of the first KK excitations

- Assume

$$\Gamma \quad \Gamma \gg \Gamma_G$$

Then we'll have the cascade decays as before

$$q_1^{\bullet} \to q\, Z_1^{*} \to q \quad l_1^{\bullet} \to q \quad \gamma$$

but in this case the LKP is stable no more

$$\to \quad G$$

The signal will be two photons + $\not{E}_T$

- The mixed case

$$\Gamma \quad \Gamma_G$$

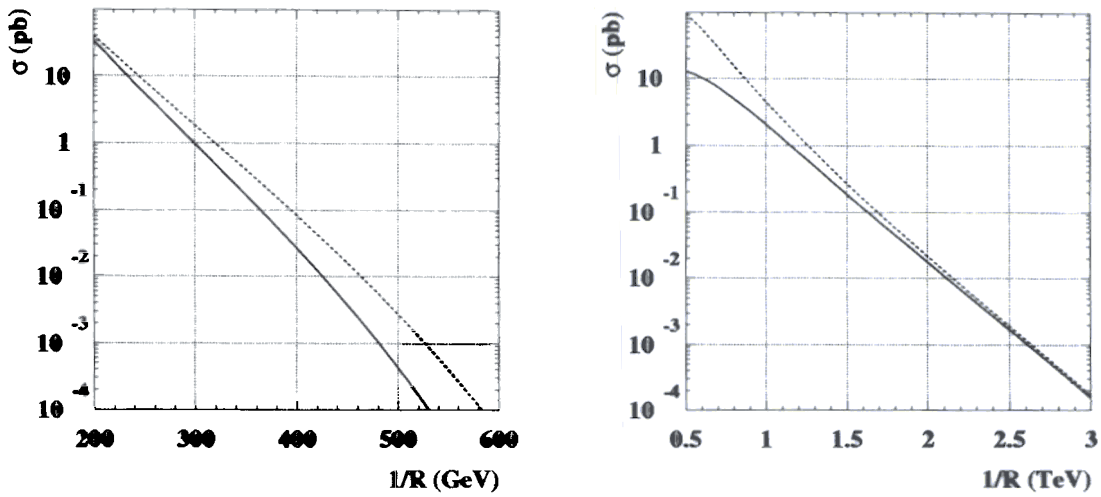
Then gravity mediated decay can take place at any step of the decay chain above.

The signal will then appear in multiple channels containing hard et ep ons and p ot ons with large $\not{E}_T$

the branching ratio for each of this channels is dependent on the parameters of the model through the t decay v d hs

Collider reach for $2\gamma + \not{E}_T$

Cross sections:



--- N = 2 — N = 6

Backgrounds:

multijet, direct photon, $W + \gamma$, W + jets, $Z \to ee$ and $Z \to \tau\tau \to ee$ with misidentified photons and/or mismeasured $\not{E}_T$

Collider reach

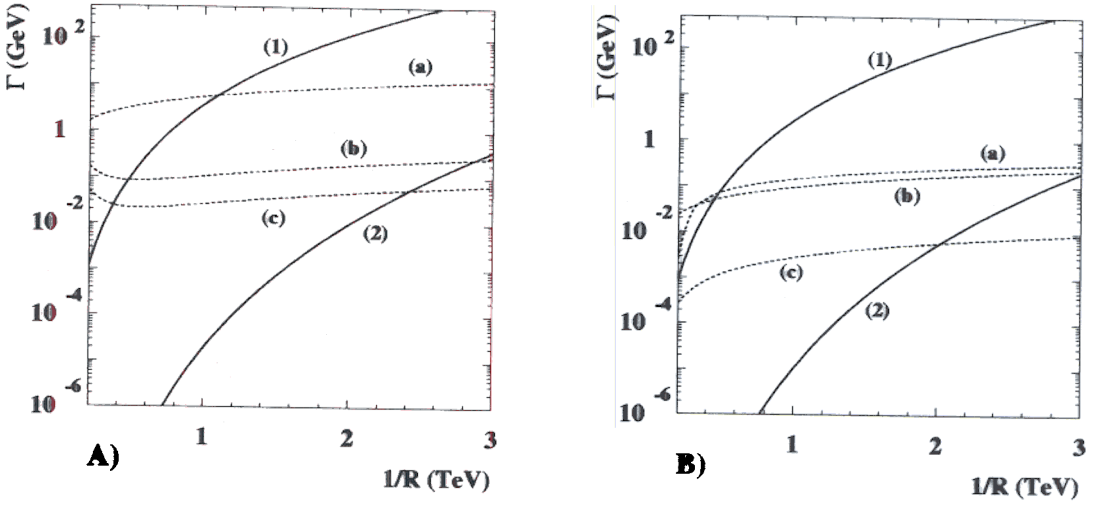
Tevatron Run I: est. bkgr: 2.3 ± 0.9 evts, found 2 events
(with $p_T^{\gamma 1} > 20$ GeV, $p_T^{\gamma 2} > 12$ GeV, and $\not{E}_T > 25$ GeV)
$\Rightarrow$ lower limit on the UED scale : $1/R > 380$ GeV (at 95%CL)

Tevatron Run II: est. bkgr: 0.6 ± 0.12 fb
(with $p_T^{\gamma 1}, p_T^{\gamma 2} > 20$ GeV, and $\not{E}_T > 25$ GeV)
$\Rightarrow$ 5σ discovery up to 490 GeV (IIA) or 520 GeV (IIB)
exclusion at 95%CL up to 510 GeV (IIA) or 540 GeV (IIB)

LHC: est. bkgr: 0.05 fb
(with $p_T^{\gamma 1}, p_T^{\gamma 2} > 200$ GeV, and $\not{E}_T > 200$ GeV)
$\Rightarrow$ reach to about 3 TeV.

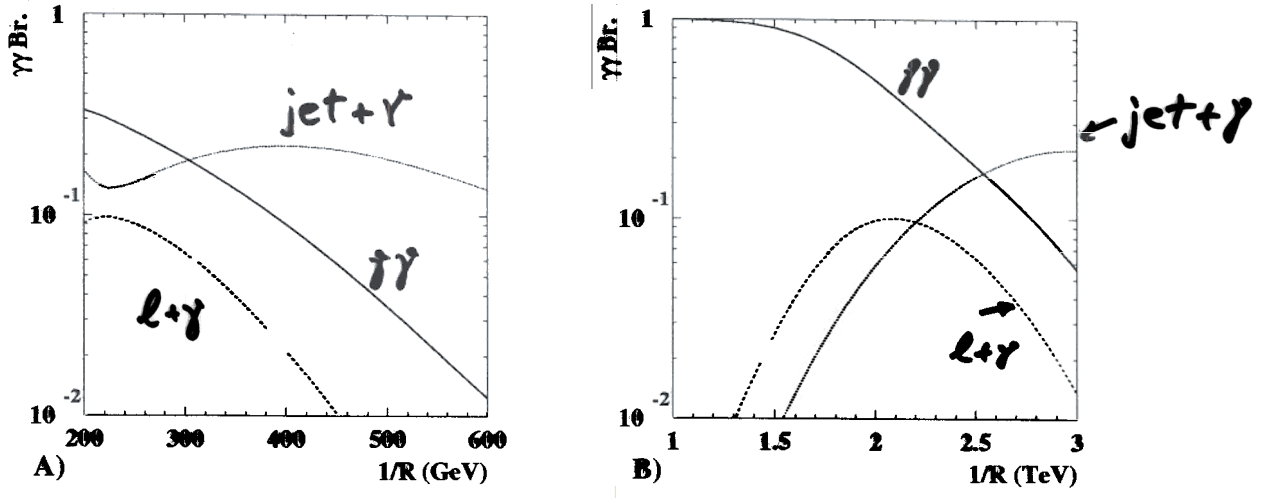
Mixed case

Decay widths: → dependent on the parameters : M_D, Λ, ...



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: $g^* \to q\bar{q}^\bullet, q\bar{q}^\circ +$ h.c. (a), $W^* \to l\bar{\nu}^\bullet, \nu\bar{l}^\bullet +$ h.c. (b), $Z^* \to l\bar{l}^\bullet +$ h.c. (c) (left), and $q^\bullet \to q'W^*, qZ^*$ (a), $q^\circ \to q\gamma^*$ (b), $l^\bullet \to l\gamma^*$ (c) (right).

Branching ratios:



Tevatron Run II, N=2
if N=6, γγ predominates

LHC, N=6
if N=6, 2jets predominates

Conclusions

looked at collider signals for Universal Extra Dimensions in a scenario with

decays induced by mass splittings

decay induced by gravity interactions

- the KK excitations decays are driven mostly by ◎, then the signal will be $2\gamma + \not{E}_T$

the decays are mostly gravity-mediated, the signal will be 2 jets + $\not{E}_T$

both cases, the phenomenology is exciting!