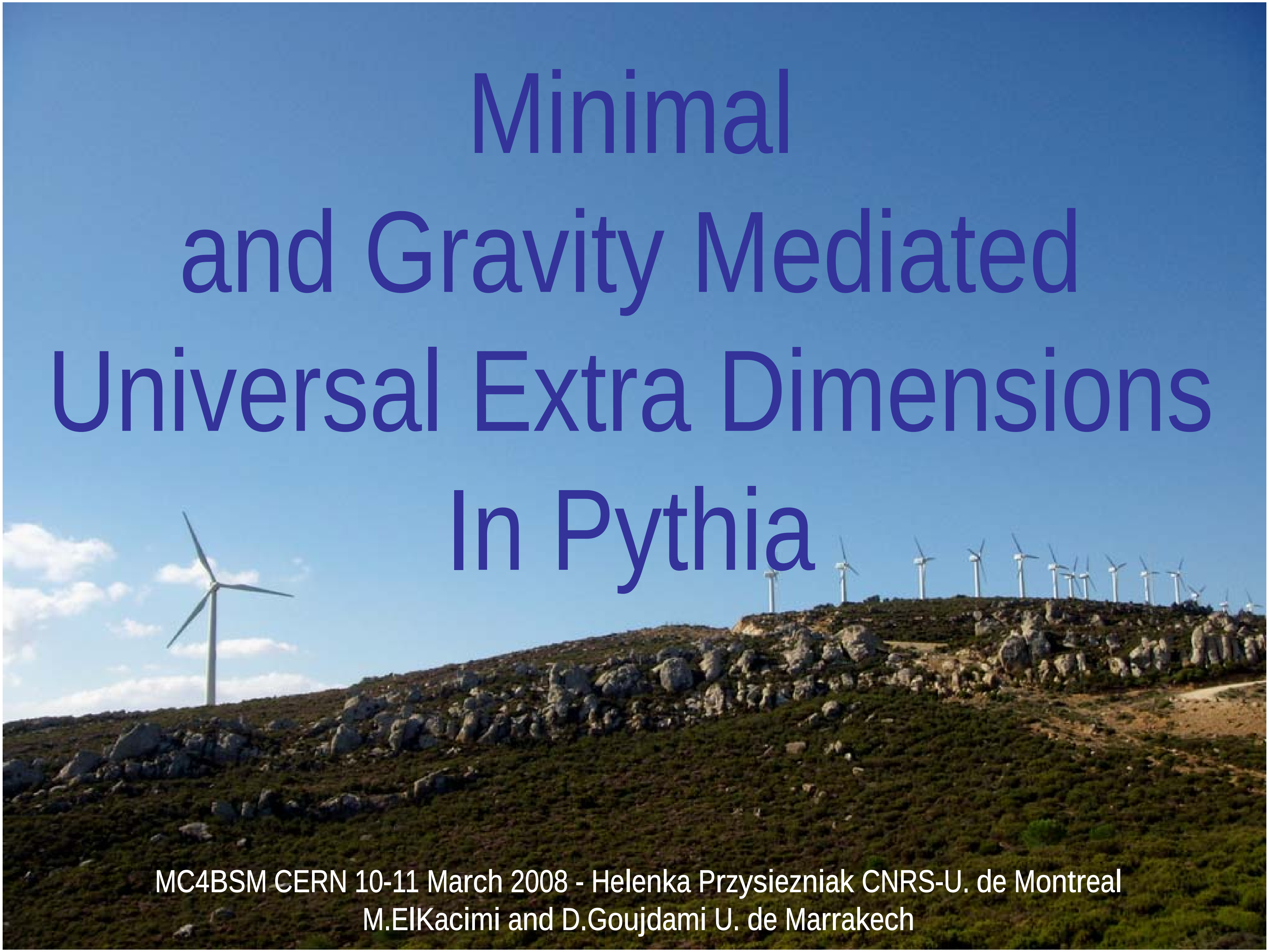

Minimal and Gravity Mediated Universal Extra Dimensions In Pythia

MC4BSM CERN 10-11 March 2008 - Helenka Przysiezniak CNRS-U. de Montreal
M.ElKacimi and D.Goujdami U. de Marrakech

UED bibliography

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P.-H.Beauchemin and G.Azuelos
ATL-PHYS-PUB-2005-003, 2005.

Before turning to Pythia,

we

(ATLAS colleagues M.ElKacimi, D.Goujdami, H.P.)

had played with

CalcHEP

(A.Pukhov)

and had used

CompHEP

(E.Boos, V.Bunichev, M.Dubinin,
L.Dudko, V.Edneral, V.Ilyin, A.Kryukov,
V.Savrin, A.Semenov, A.Sherstnev)

for generation of UED LesHouches format 4-vector files.

Many thanks to the authors!

This lead us to modify PYTHIA such that it can now generate UED events.

At first we called it

PYTHIA_UED

during the Les Houches Workshops.

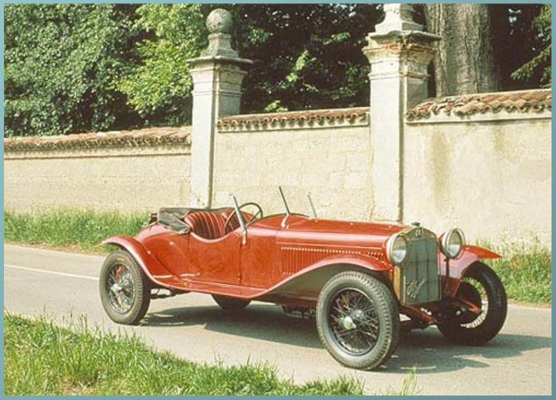
Many thanks to the PYTHIA authors, in particular the CERN based one (s) !

The Universal Extra Dimensions model

“solves” some known problems
(gauge couplings unification,
symmetry breaking at the TeV,
fermion masses hierarchy,
Higgs doublet generation,…)

AND

mocks the MSSM rather well.



A review of the Universal Extra Dimensions (UEDs) model

“Universal” == ALL SM particles propagate into the XtraD(s)

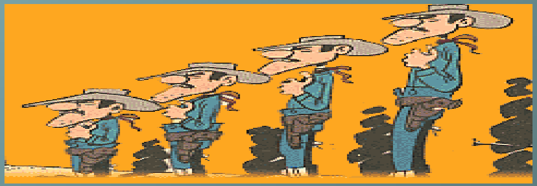
n=1,2,3,… Kaluza Klein (KK) excitations
for each SM particle of mass

$$m_n^2 = n^2/R^2 + m_{SM}^2$$

n=0 corresponds to the SM particle
R : compactification scale
Λ : cutoff scale above which the theory is no longer valid

Momentum is conserved in the extra dimensions.
In 3D (3D+t), this implies conservation of the KK number :

• never a vertex with only one KK excitation
• KK particles are always produced in pairs



A bit of UED Zoology

Q ("D"oublet), U and D ("S"inglets) fields describe the quarks in $(4+\delta)$ dimensions

e.g. for the 3rd generation first level particles

$Q^{(0)}_3 \equiv (t,b)_L$

$U^{(0)}_3 \equiv t_R$ and $D^{(0)}_3 \equiv b_R$

For each fermion 1 tower/chiral state ==

2 towers/quark flavor

2 towers/massive-lepton

1 tower/massless-neutrino

Bosons W^{3j}_μ and B^j_μ mix within each level, as in the SM (level 0).

Each Higgs boson KK level is composed of :

1 charged Higgs

1 scalar CP-odd Higgs of mass M_j

1 scalar CP-even of mass $\sqrt{(M^2_j+m^2_h)}$

The interactions between the Higgs field,

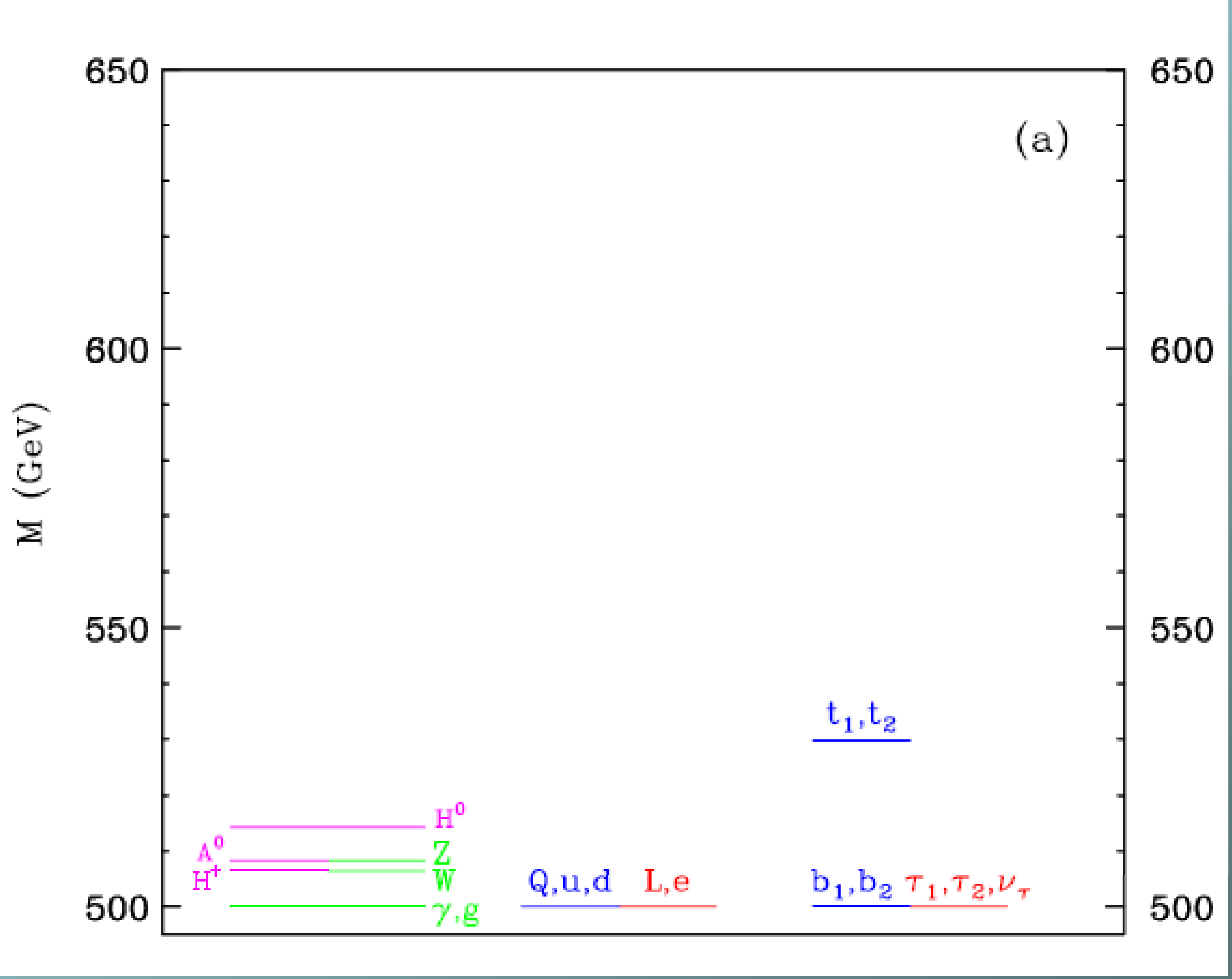
the gauge bosons and the fermions

are described by the same couplings as those for the SM

“n=1” KK states – a very degenerate situation

All particles have practically the same mass == 1/R (compactification scale)

Below : 1/R = 500 GeV



Radiative Corrections – larger mass splittings

KK number is conserved at tree level, but can be violated in first order loops

First order corrections can bring large contributions to the KK masses.
Tree level radiative corrections
~20% for strongly interacting particles (heaviest being the gluon)
<10% for leptons and EW bosons (lightest being the photon)

SM quark and gluon KK excitations will cascade decay to the
Lightest Kaluza Klein Particle (LKP) : γ^*

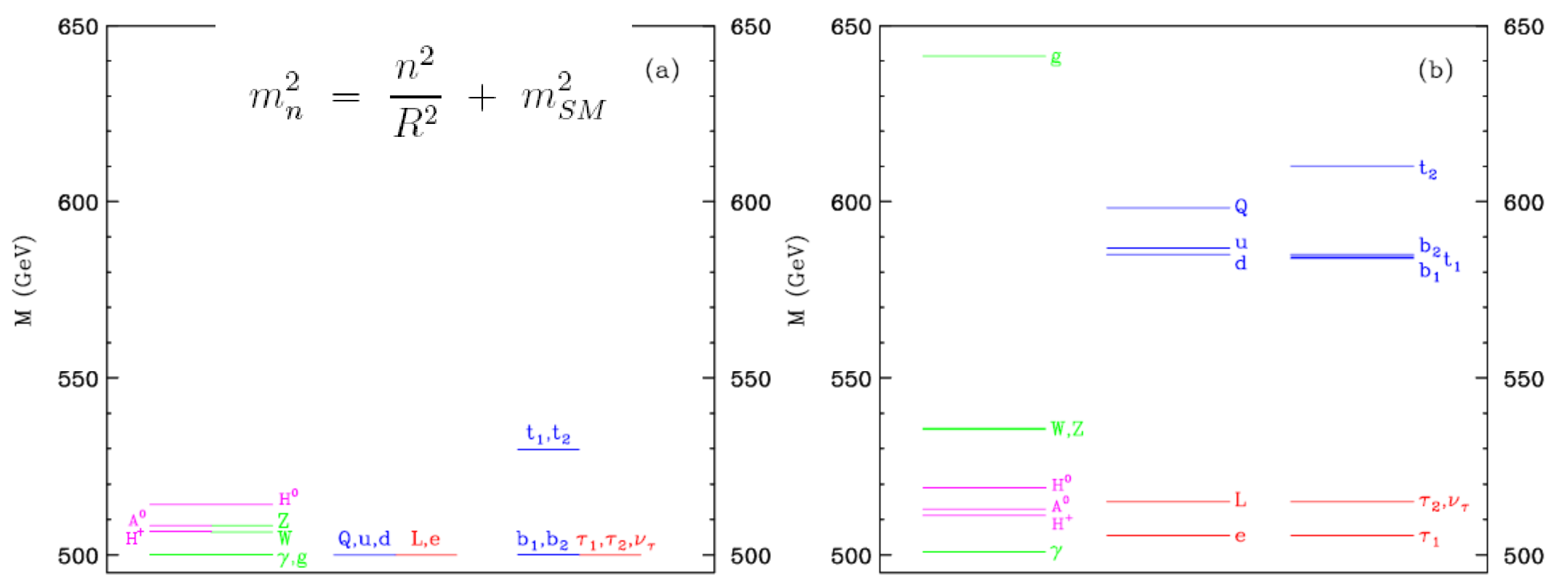


FIG. 6: The spectrum of the first KK level at (a) tree level and (b) one-loop, for $R^{-1} = 500$ GeV, $\Lambda R = 20$, $m_h = 120$ GeV, $\overline{m}_H^2 = 0$, and assuming vanishing boundary terms at the cut-off scale Λ.

Minimal UED scenario

Fermions and bosons live in a
$4+\delta$ ($R \sim TeV^{-1}$) dimensional "thick" brane.
Minimal is the $\delta = 1$ case.

+ Gravity mediated decays

The "thick brane" (of dimension $4+\delta$) where the SM particles propagate
is embedded in a larger space of (4+N) dimensions (1/R~eV) where only gravitons propagate.

The graviton field appears as a massless graviton
with an infinity of excited modes whose masses differ by 1/R~eV (infinite KK tower).

The graviton couples to all KK particles,
which can decay through KK number violating interactions mediated by gravity,
by emitting a graviton
e.g. LKP : $\gamma^* \to \gamma G$

There is henceforth an interplay between the mass splitting and the gravity mediated decay widths.
e.g. if Γ(mass splitting) $\gg$ Γ(gravity mediated)
gluon and quark excitations cascade decay down to the γ^*
which in turn will decay as
$\gamma^* \to \gamma G$

Pythia_UED soon to be in Pythia 6.4.16

- UED particle spectrum and production mechanisms differential cross sections

MSEL=100 :	$g + g \rightarrow g^* + g^*$	(ISUB=311)
	$g + g \rightarrow$ Dq + Dqbar, Sq + Sqbar	(ISUB=314)
MSEL = 101 :	$g + q \rightarrow g^*$ + Dq/Sq	(ISUB=312)
MSEL = 102 :	$q + q' \rightarrow$ Dq + Dq’, Sq + Sq’	(ISUB=313)
	q + qbar $\rightarrow$ Dq + Dqbar, Sq + Sqbar	(ISUB=315)
	q + qbar’ $\rightarrow$ Dq + Sqbar’	(ISUB=316)
	q + qbar’ $\rightarrow$ Dq + Dqbar’, Sq + Sqbar’	(ISUB=317)
	$q + q' \rightarrow$ Dq + Sq’	(ISUB=318)
	q + qbar $\rightarrow$ Dq’ + Dqbar’	(ISUB=319)

- Graviton mass distribution
- Radiative corrections to the particle masses and partial decay widths
- Gravitational decay widths (e.g.for $\gamma^* \rightarrow \gamma G$) and graviton mass expression

Modifications to Pythia

(many thanks to the Pythia authors, in particular the CERN based one (s)!!)

MODIFIED ROUTINES

pydata.f (declares all Pythia vectors-matrices needed;
modified to include the UED particles and production and decay processes)

pyofsh.f (computes partial widths and differential Xsection maxima
for channels/processes not allowed on mass-shell,
and selects masses in such channels/processes;
modified to include KK particles)

pyscat.f (finds outgoing flavours and event type;
sets up the kinematics and colour flow of the hard scattering;
modified to include UED hard scatt. procs→see MSEL in previous page)

pywidt.f (called by pysghg_ChL.f and pyresd.F; computes full/partial widths of resonances;
in UED, the mass splitting and gravity mediated decay widths)

pysigh.f (differential matrix elements for all included subprocesses;
makes a map of procs indicating which routine to call to evaluate the Xsec;
map modified to include UED processes)

NEW ROUTINES

pygram.f (computes graviton mass; called by pyxdin→initialization and by pyevnt.f)

pyxdin.f (computes KK masses and and calls the widths calculations; called by pyinit.f)

pyuexd.f (called by pysigh; computes UED diff. Xsecs)

pygrav.f (computes gravity mediated partial decay widths)

Production cross sections

pp →g*g*,g*q*,q*q*→ KK + KK

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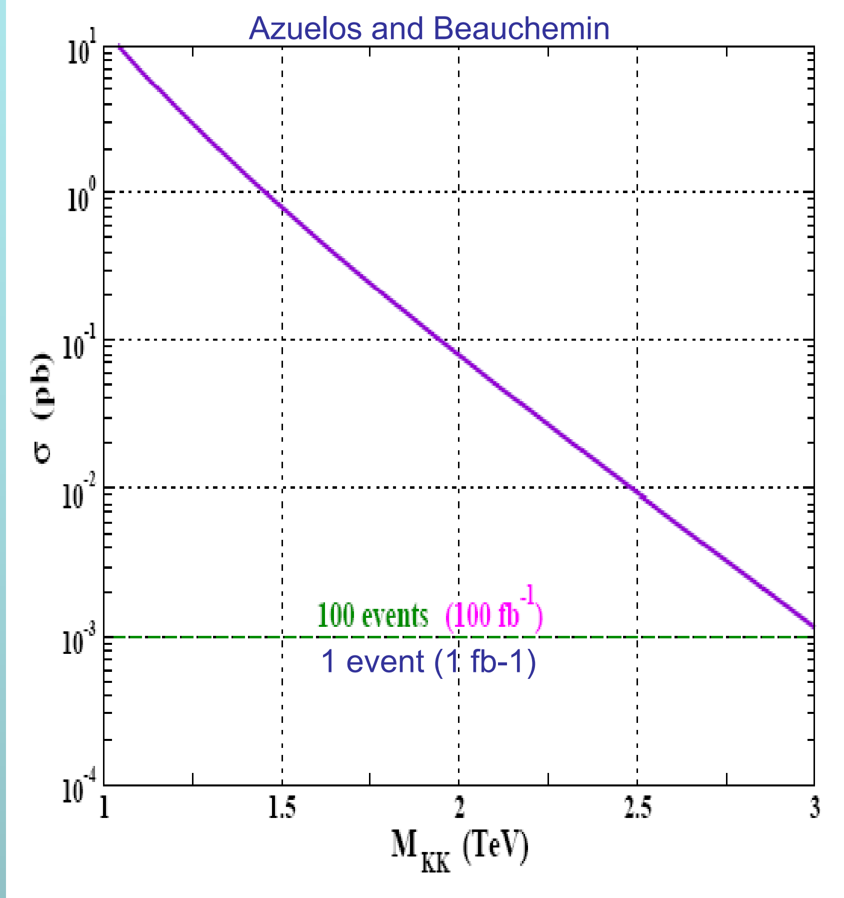
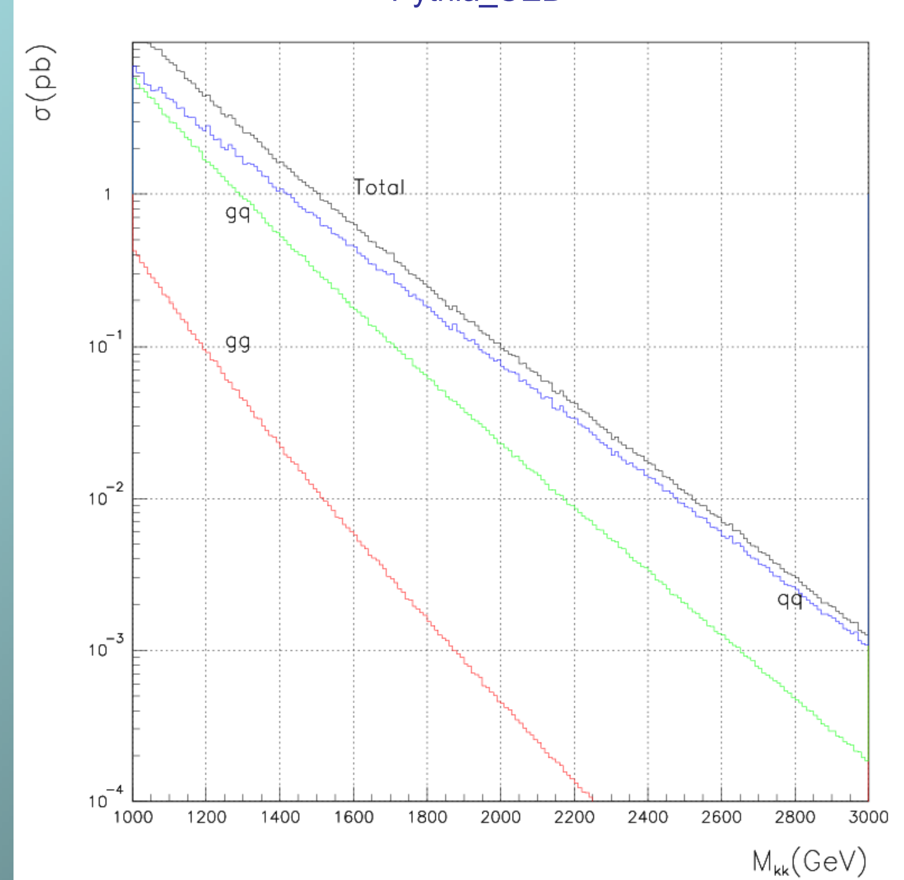


Pythia_UED



Blue: initial state quark pair

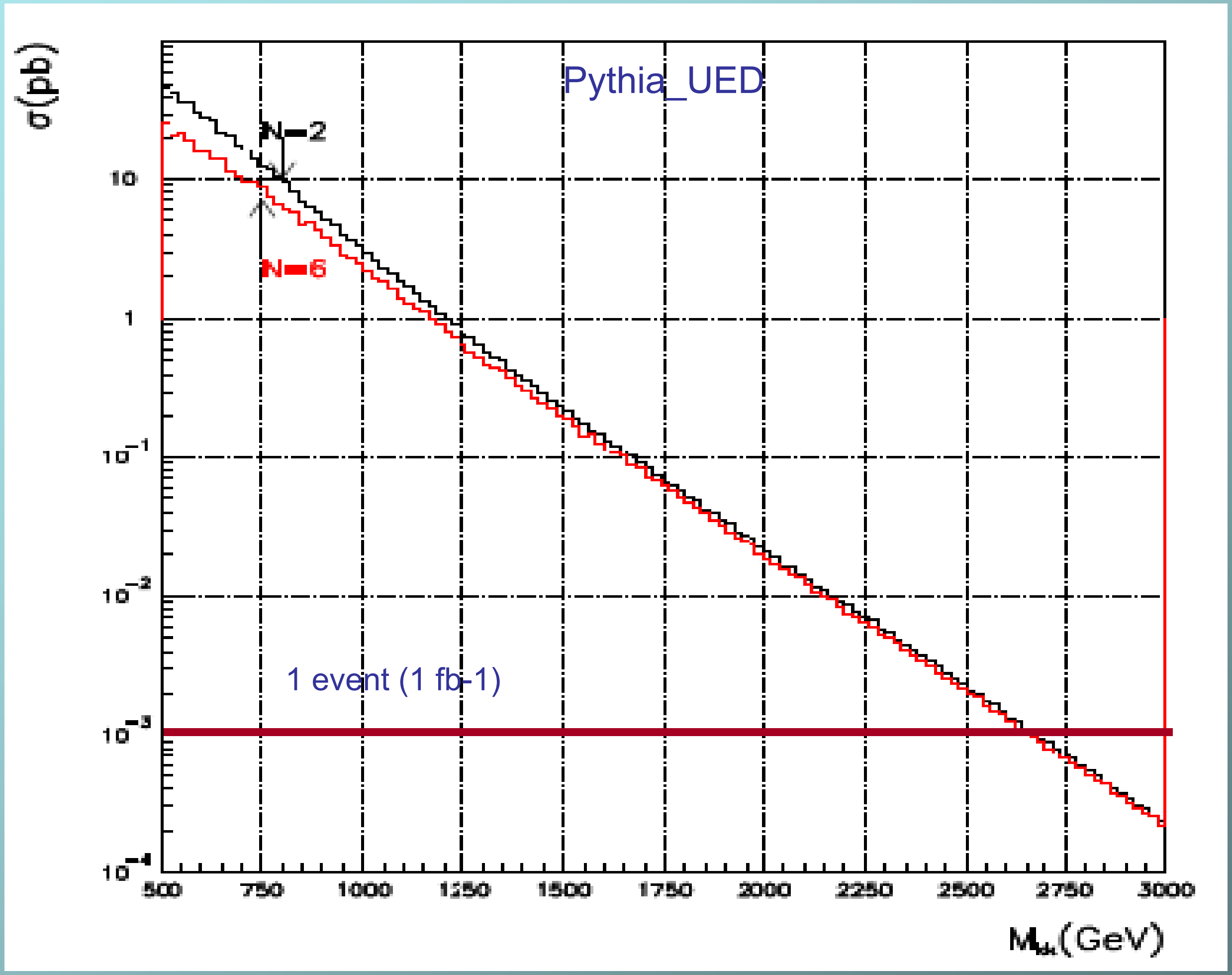
Green: initial state quark-gluon

Red: initial state gluon pair

Solid line: sum of all

Production cross sections

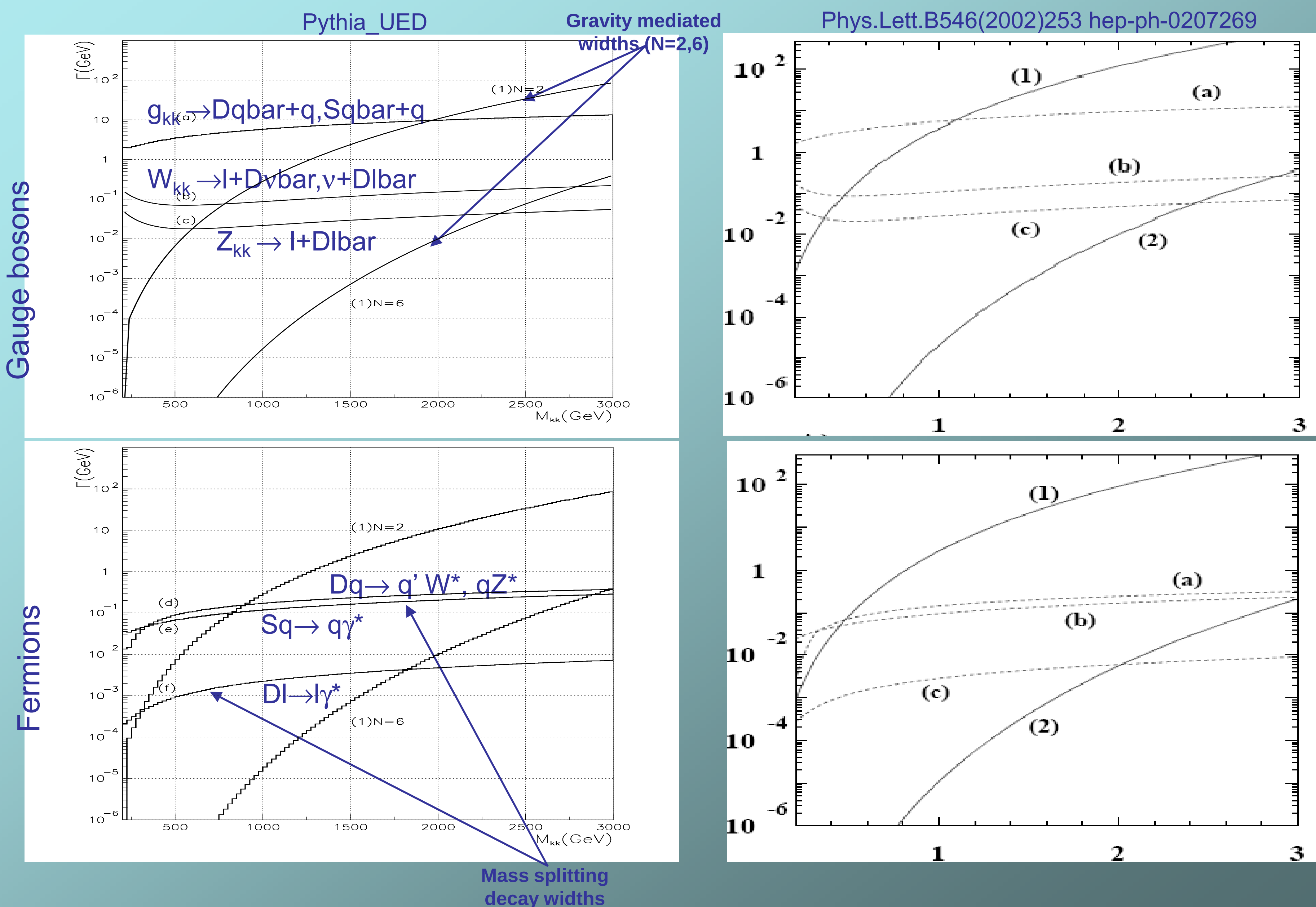
pp $\rightarrow$g*g*,g*q*,q*q* $\rightarrow$ KK + KK$\rightarrow$ γ* + γ* + X$\rightarrow$ γ + γ + X'



√s =14TeV
Pt_{γ} >200GeV
Etmiss > 200 GeV
$|\eta_{\gamma}|$ < 2.5
CTEQ5L
N=2,6

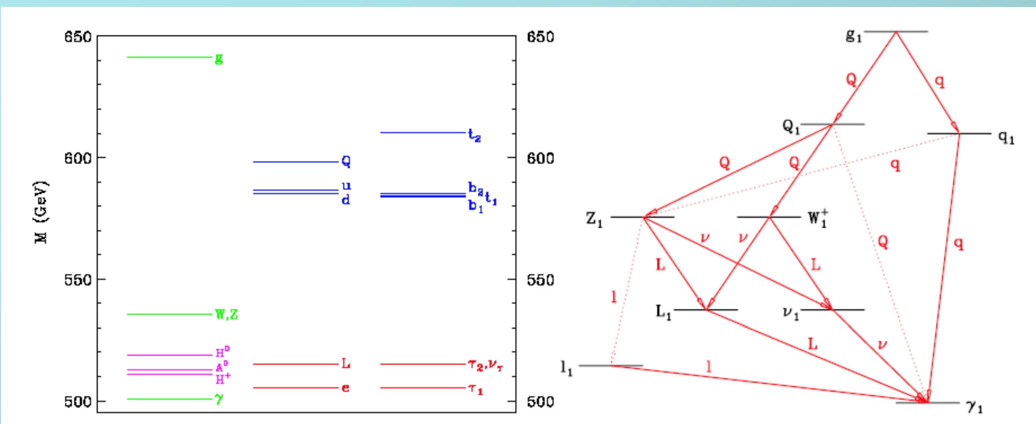
With 1fb-1
~250 evts (1/R=1.5TeV) ~>2500 evts (1/R=1TeV)
N.B. Photon detection efficiency~80% (not included in this plot)
Cuts efficiency ~10-50% e.g. Rinv=1000 pT>200GeV Eff=30% (included in this plot)
Background : small ? (not included in this plot; estimated to be 0.05 fb)

Decay widths for bosons and fermions



Decay processes

mass splitting decays



$Sq(\ell) \rightarrow q(\ell)\ \gamma^*$

$D\ell \rightarrow \ell\ \gamma^*$

$Dq \rightarrow q\ \gamma^*$

$Dq \rightarrow q\ Z^* \rightarrow q\ \ell\ D\ell \rightarrow q\ \ell\ \ell\ \gamma^*$

$(Z^* \rightarrow \ell\ D\ell)$

$Dq \rightarrow q\ W^* \rightarrow q\ \ell'\ D\ell \rightarrow q\ \ell'\ \ell\ \gamma^*$

$(W \rightarrow \ell'\ D\ell)$

gravity mediated decays

$Sq(\ell)$	$\rightarrow q(\ell)$ Graviton
$Dq(\ell)$	$\rightarrow q(\ell)$ G
γ^*	$\rightarrow \gamma$ G
W*	$\rightarrow$ W G
Z*	$\rightarrow$ Z G
g*	$\rightarrow$ g G

Summary and outlook

Minimal and
gravity mediated UED
almost in Pythia 6.4.16.

Validation tests
have been performed,
and also
within the ATLAS environment.

Could we have a Pythia
generating UED events
before the LHC turns on?

XtraDs around the corner?

UED - Cosmological Aspects
(the need? for gravity mediated decays)

Existence of new particles $\rightarrow$ cosmological problems
If some of these survive at the moment of nucleosynthesis,
they could combine with other nuclei and form heavy hydrogen atoms.
Such isotopes have been searched for but not found.
In addition, many cosmological arguments
exclude the existence of particles with masses 100 GeV $\rightarrow$ 10 TeV.

These problems can be avoided if KK number violation occurs, causing LKP decay.
The lifetime depends on the strength of the KK number violating interactions,
usually suppressed by the cutoff scale and/or the size of the XtraDs.

A solution: gravity mediated decays

Cosmological Aspects

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These problems can be avoided if KK number violation occurs, causing LKP decay.
A solution: gravity mediated decays

Br. = 100%	$q^{\circ} \rightarrow q\ \gamma^*$
Br. = 100%	$\ell^{\circ} \rightarrow \ell\ \gamma^*$
Br. = 100%	$\ell^{\bullet} \rightarrow \ell\ \gamma^*$
Br. ~ 2%	$q^{\bullet} \rightarrow q\ \gamma^*$
Br. ~ 33%	$q^{\bullet} \rightarrow q\ Z^* \rightarrow q\ \ell\ \ell^{\bullet} \rightarrow q\ \ell\ \ell\ \gamma^*$
Br. ~ 65%	$q^{\bullet} \rightarrow q\ W^* \rightarrow q\ \ell'\ \ell^{\bullet} \rightarrow q\ \ell'\ \ell\ \gamma^*$
Br. ~ 100%	$\gamma^* \rightarrow \gamma\ G$

Lagrangian

(Bound on Universal Extra Dimensions hep-ph/0012100 Appelquist, Cheng and Dobrescu)

space-time coordinates, x^μ, $\mu = 0, 1, 2, 3$, and the coordinates of the extra dimensions, y^a, $a = 1, ..., \delta$. The 4-dimensional Lagrangian can be obtained by dimensional reduction from the $(4+\delta)$-dimensional theory,

$$\begin{aligned}\mathcal{L}(x^\mu) &= \int d^\delta y \left\{ -\sum_{i=1}^{3} \frac{1}{2\hat{g}_i^2} \mathrm{Tr}\left[F_i^{\alpha\beta}(x^\mu, y^a) F_{i\,\alpha\beta}(x^\mu, y^a) \right] + \mathcal{L}_{\mathrm{Higgs}}(x^\mu, y^a) \right. \\ &+ i \left(\overline{\mathcal{Q}}, \overline{\mathcal{U}}, \overline{\mathcal{D}} \right) (x^\mu, y^a) \left(\Gamma^\mu D_\mu + \Gamma^{3+a} D_{3+a} \right) (\mathcal{Q}, \mathcal{U}, \mathcal{D})^\top (x^\mu, y^a) \\ &\left. + \left[\overline{\mathcal{Q}}(x^\mu, y^a) \left(\hat{\lambda}_{\mathcal{U}} \mathcal{U}(x^\mu, y^a) i\sigma_2 H^*(x^\mu, y^a) + \hat{\lambda}_{\mathcal{D}} \mathcal{D}(x^\mu, y^a) H(x^\mu, y^a) \right) + \mathrm{h.c.} \right] \right\} \quad (2.1)\end{aligned}$$

Here $F_i^{\alpha\beta}$ are the $(4+\delta)$-dimensional gauge field strengths associated with the $SU(3)_C \times SU(2)_W \times U(1)_Y$ group, while $D_\mu = \partial/\partial x^\mu - \mathcal{A}_\mu$ and $D_{3+a} = \partial/\partial y^a - \mathcal{A}_{3+a}$ are the covariant derivatives, with $\mathcal{A}_\alpha = -i \sum_{i=1}^{3} \hat{g}_i \mathcal{A}_{\alpha i}^r T_i^r$ being the $(4+\delta)$-dimensional gauge fields. The piece $\mathcal{L}_{\mathrm{Higgs}}$ of the $(4+\delta)$-dimensional Lagrangian contains the kinetic term for the $(4+\delta)$-dimensional Higgs doublet H, and the Higgs potential. The $(4+\delta)$-dimensional gauge couplings $\hat{g}_i$, and the Yukawa couplings collected in the 3×3 matrices $\hat{\lambda}_{\mathcal{U},\mathcal{D}}$, have dimension $(\mathrm{mass})^{-\delta/2}$.

The fields $\mathcal{Q}, \mathcal{U}$ and $\mathcal{D}$ describe the $(4+\delta)$-dimensional fermions whose zero-modes are given by the 4-dimensional standard model quarks. A summation over a generational index is implicit in Eq. (2.1). For example, the 4-dimensional, third generation quarks may be written as $\mathcal{Q}_3^{(0)} \equiv (t, b)_L$, $\mathcal{U}_3^{(0)} \equiv t_R$, $\mathcal{D}_3^{(0)} \equiv b_R$. The kinetic and Yukawa terms for

Radiative corrections – bulk and boundary terms

Radiative corrections to Kaluza-Klein masses

hep-ph/0204342 Cheng, Matchev, Schmaltz

Bulk corrections

$$\delta(m_{B_n}^2) = -\frac{39}{2}\frac{g'^2\zeta(3)}{16\pi^4}\left(\frac{1}{R}\right)^2,$$

$$\delta(m_{W_n}^2) = -\frac{5}{2}\frac{g_2^2\zeta(3)}{16\pi^4}\left(\frac{1}{R}\right)^2,$$

$$\delta(m_{g_n}^2) = -\frac{3}{2}\frac{g_3^2\zeta(3)}{16\pi^4}\left(\frac{1}{R}\right)^2,$$

$$\delta(m_{f_n}) = 0,$$

$$\delta(m_{H_n}^2) = 0,$$

Boundary terms

$$\bar{\delta} m_{Q_n} = m_n\left(3\frac{g_3^2}{16\pi^2} + \frac{27}{16}\frac{g_2^2}{16\pi^2} + \frac{1}{16}\frac{g'^2}{16\pi^2}\right)\ln\frac{\Lambda^2}{\mu^2},$$

$$\bar{\delta} m_{u_n} = m_n\left(3\frac{g_3^2}{16\pi^2} + \frac{g'^2}{16\pi^2}\right)\ln\frac{\Lambda^2}{\mu^2},$$

$$\bar{\delta} m_{d_n} = m_n\left(3\frac{g_3^2}{16\pi^2} + \frac{1}{4}\frac{g'^2}{16\pi^2}\right)\ln\frac{\Lambda^2}{\mu^2},$$

$$\bar{\delta} m_{L_n} = m_n\left(\frac{27}{16}\frac{g_2^2}{16\pi^2} + \frac{9}{16}\frac{g'^2}{16\pi^2}\right)\ln\frac{\Lambda^2}{\mu^2},$$

$$\bar{\delta} m_{e_n} = m_n\frac{9}{4}\frac{g'^2}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2},$$

$$\bar{\delta}(m_{B_n}^2) = m_n^2\left(-\frac{1}{6}\right)\frac{g'^2}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2},$$

$$\bar{\delta}(m_{W_n}^2) = m_n^2\frac{15}{2}\frac{g_2^2}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2},$$

$$\bar{\delta}(m_{g_n}^2) = m_n^2\frac{23}{2}\frac{g_3^2}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2},$$

$$\bar{\delta}(m_{H_n}^2) = m_n^2\left(\frac{3}{2}g_2^2 + \frac{3}{4}g'^2 - \lambda_H\right)\frac{1}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2} + \overline{m}_H^2.$$

Radiative corrections - Higgses

Radiative corrections to Kaluza-Klein masses
hep-ph/0204342 Cheng, Matchev, Schmaltz

Finally we discuss the KK modes of the Higgs field. The KK modes of W and Z acquire their masses by "eating" linear combinations of the fifth component of the gauge fields and the Higgs KK modes. The orthogonal combinations remain physical scalar particles. For $1/R \gg M_{W,Z}$, the longitudinal components of the KK gauge bosons mostly come from A_5, and the physical scalars are approximately the KK excitations of the Higgs field. There are 4 states at each KK level, $H_n^{\pm}, H_n^0, A_n^0$ (notice that $H_0^{\pm}$ and A_0^0 are just the usual Goldstone bosons in the SM). Their corrected masses are given by

$$
\begin{aligned}
m_{H_n^0}^2 &\approx m_n^2 + m_h^2 + \hat{\delta} m_{H_n}^2 \\
m_{H_n^{\pm}}^2 &\approx m_n^2 + M_W^2 + \hat{\delta} m_{H_n}^2 \qquad (48) \\
m_{A_n^0}^2 &\approx m_n^2 + M_Z^2 + \hat{\delta} m_{H_n}^2 .
\end{aligned}
$$

Gravity mediated decay of the LKP

code from P.-H. Beauchemin and G.Azuelos, ATL-PUB-PHYS-2005-003

gravity mediated decay of KK photon
$\gamma^* \rightarrow \gamma G$
using proper integration over all graviton KK states

For the LKP decay, sum up the graviton towers by following the analyses in
G.F.Giudice, R.Rattazzi, J.D.Wells, Nucl. Phys. B544, 3 (1999);
T.Han, J.D.Lykken, R-.J. Zhang, Phys. Rev. D59, 105006 (1999).
Result should be relatively independent of the spin of the original KK state.
The total width is given by

$$\Gamma = \frac{(2\pi)^{\delta/2}\ \overline{M}_{Pl}^2}{\Gamma(\delta/2)\ M_D^{2+\delta}} \int_{R_G^{-1}}^{M_{KK}} dm_g\ m_g^{\delta-1}\ \Gamma(m_g)\ [\mathcal{F}(m_g R_c)]^2 (n=1)$$

where $\Gamma(m_g)$ is the width for the decay into a graviton of mass m_g
M_D is the 4+δ Planck scale,
M_{Pl} is the conventional 4-d reduced Planck scale,
and M_{KK} is the mass of the relevant decaying KK state.

Gravity mediated decay of the LKP

The graviton is decomposed into 4D tensor(h), vector(A) and scalar components(phi).

The decay widths to a single graviton are given below. For the decay of a KK fermion:

$$\Gamma(q^l \to q h^{\bar{n}}) = |\mathcal{F}^c_{l|n}|^2 \frac{\kappa^2}{2\times 384\pi} \frac{M^3}{x^4} \left[\left(1-x^2\right)^4 \left(2+3x^2\right) \right]$$

$$\Gamma(q^l \to q A^{\bar{n}}) = |\mathcal{F}^c_{l|n}|^2 \frac{\kappa^2}{2\times 256\pi} M^3 \left[\left(1-x^2\right)^2 \left(2+x^2\right) \right] \times P_{55}$$

$$\Gamma(q^l \to q \phi^{\bar{n}}) = |\mathcal{F}^c_{l|n}|^2 \frac{\kappa^2}{2\times 256\pi} M^3 \left(1-x^2\right)^2 \left[c_{11} \frac{(1-x^2)^2}{x^4} + 2c_{12} \frac{1-x^2}{x^2} + c_{22} \right] \quad (25)$$

For the decay of a KK gauge boson excitation, the following results are obtained:

$$\Gamma(B^l \to B h^{\bar{n}}) = |\mathcal{F}^c_{l|n}|^2 \frac{\kappa^2}{3\times 96\pi} \frac{M^3}{x^4} \left[\left(1-x^2\right)^3 \left(1+3x^2+6x^4\right) \right]$$

$$\Gamma(B^l \to B A^{\bar{n}}) = |\mathcal{F}^c_{l|n}|^2 \frac{\kappa^2}{3\times 32\pi} \frac{M^3}{x^2} \left[\left(1-x^2\right)^3 \left(1+x^2\right) \right] \times P_{55}$$

$$\Gamma(B^l \to B \phi^{\bar{n}}) = |\mathcal{F}^c_{l|n}|^2 \frac{\kappa^2}{3\times 32\pi} M^3 \left(1-x^2\right)^3 \left[c_{11} \frac{1}{x^4} + 2c_{12} \frac{1}{x^2} + c_{22} \right] \quad (27)$$

Gravity mediated decay of the LKP

In order to obtain the total gravitational decay width for a KK excitation, a sum over KK gravitons with mass smaller than the mass of the decaying particle has to be performed. Since the masses of the graviton KK excitations are closely spaced, this sum can be replaced

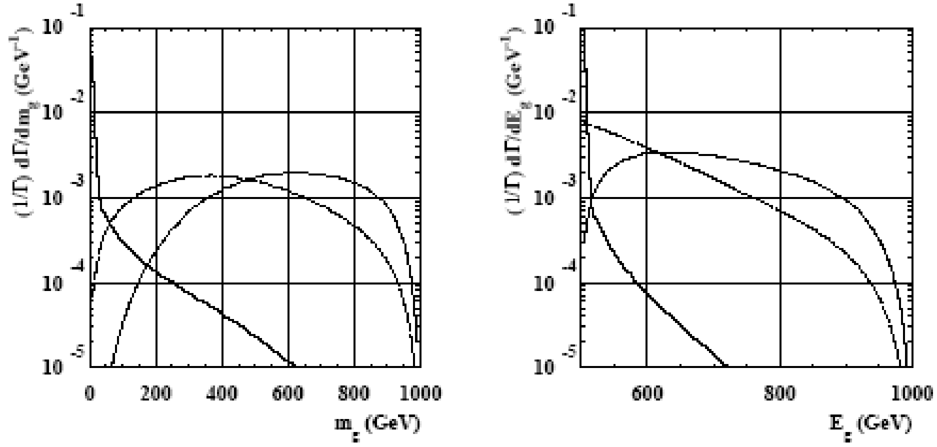

Figure 3: Mass distribution (left) and energy distribution (right) for the graviton radiated in the decay of one matter KK excitation with mass 1 TeV. Straight lines corresponds to $N = 2$ extra dimensions, dashed lines to $N = 4$, and dotted lines to $N = 6$.

by an integral over the graviton density of states (for more details, see [12, 10]). The results obtained for some values of the model parameters are presented in Fig. 2.

The distributions of the mass and energies of gravitons contributing to the decay of a KK excitations follow the pattern described in [10]. That is, for $N = 2$, the decay is mediated mostly by light gravitons, and the missing energy (the energy taken away by the graviton) is about half the particle mass. For higher N, more massive gravitons contribute to the total decay width, and the missing energy increases to values close to the KK particle mass, as in Fig. 3.

Decay widths for bosons and fermions

N.B.

For N=6 and up to 1/R~2.5TeV,
the KK particles will cascade decay down to the LKP
and the LKP will decay into γ + graviton,
giving a 2 photon + missing Et + soft jets,leptons signal.

For N=2 and 1/R<500 GeV,
the same will happen.

But for N=2 and 1/R>1000 GeV,
all KK particles will decay gravitationally,
and we will end up with (leptons and/or jets and/or photons) + missing Et signal
which will be difficult to analyze.

For our analysis,
we have considered the N=6 case
where all events give : two photon + missing Et + soft jets and leptons

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 Λ (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.

New Signal for UED, Phys.Lett.B546 (2002) 253, hep-ph/0207269