Physics in extra dimensions: lecture #2

Bogdan Dobrescu (*Fermilab*)

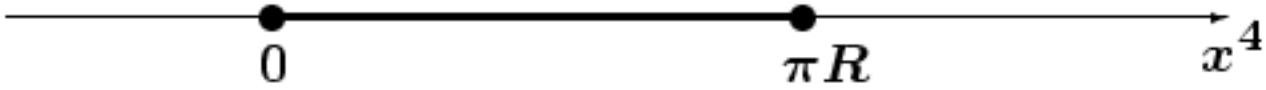
Lecture 1: Field theory in compact dimensions.
Gauge bosons in the bulk and their collider signatures.

Lecture 2: **One universal extra dimension.**
Discrete symmetries and cascade decays at colliders.

Lecture 3: Two universal extra dimensions.

Lecture 4: Particles in a warped extra dimension.

Kaluza-Klein spectrum of quarks and leptons



If standard model fermions propagate along the extra dimension, then the compactification must be on an interval

(circle compactification gives vectorlike zero-modes, not compatible with the observed fermions which are chiral).

$(t_L^{(3)}, b_L^{(3)})$ —— $\frac{3}{R}$ —— $(T_R^{(3)}, B_R^{(3)})$ $\qquad$ $T_L^{(3)}$ —— $\frac{3}{R}$ —— $t_R^{(3)}$

$(t_L^{(2)}, b_L^{(2)})$ ═══ $\frac{2}{R}$ ═══ $(T_R^{(2)}, B_R^{(2)})$ $\qquad$ $T_L^{(2)}$ ═══ $\frac{2}{R}$ ═══ $t_R^{(2)}$

$(t_L^{(1)}, b_L^{(1)})$ —— $\frac{1}{R}$ —— $(T_R^{(1)}, B_R^{(1)})$ $\qquad$ $T_L^{(1)}$ —— $\frac{1}{R}$ —— $t_R^{(1)}$

(t_L, b_L) —— $\qquad$ —— t_R

Universal Extra Dimensions

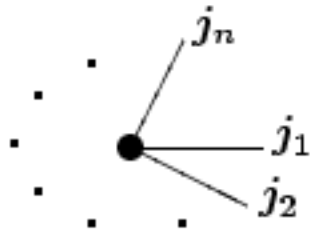
T. Appelquist, H.-C. Cheng, B. Dobrescu, Phys.Rev.D64 (2001)

All Standard Model particles propagate in $D \geq 5$ dimensions.

Kaluza-Klein modes are states of definite momentum along the compact dimensions.

Momentum conservation → KK-number conservation

$$\mathcal{L}_{4D} = \int_0^{\pi R} dx^4 \, \mathcal{L}_{5D}$$



At each interaction vertex:

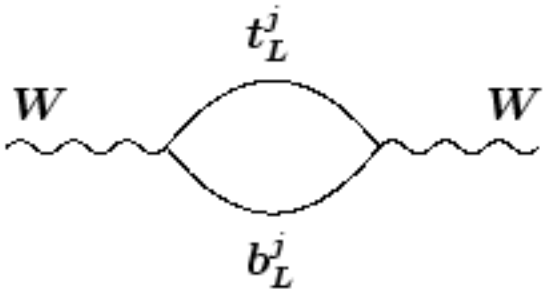
$j_1 \pm j_2 \pm ... \pm j_n = 0$ **for a certain choice of** $\pm$

In particular: $0 \pm \cdots \pm 0 \neq 1$

$\Rightarrow$ tree-level exchange of KK modes does not contribute to currently measurable quantities

$\Rightarrow$ no single KK 1-mode production at colliders

Bounds from one-loop shifts in W and Z masses, and other observables:

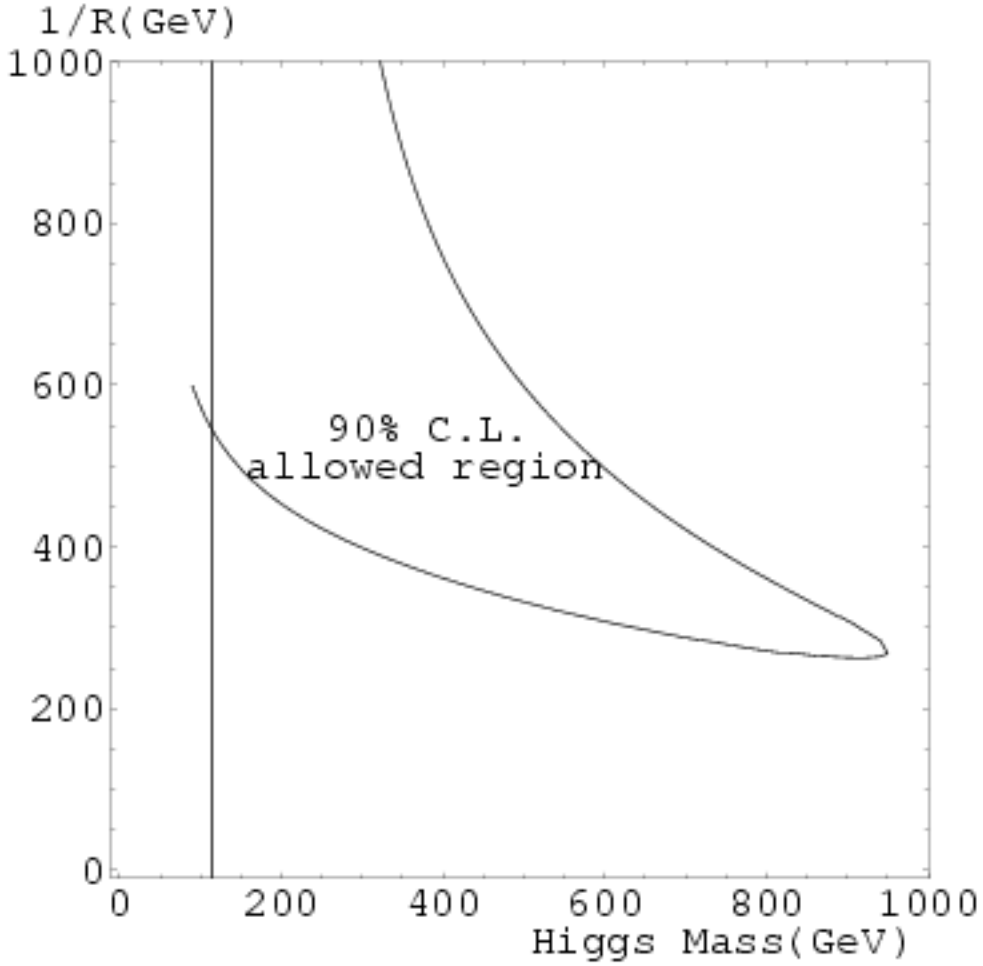


$$\frac{1}{R} \gtrsim 300 - 500 \text{ GeV}$$

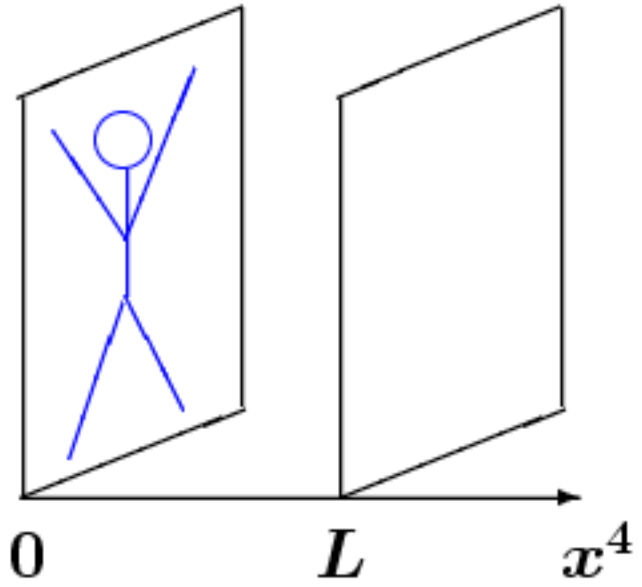
Is the Higgs boson light?

Contributions to the T parameter from Kaluza-Klein particles may compensate for the effect of a heavy Higgs boson on the electroweak fits.

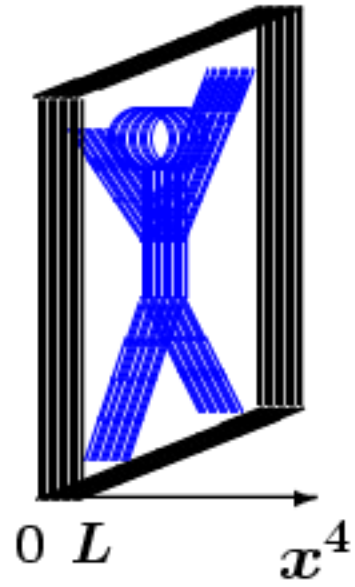
Appelquist, Yee, hep-ph/0211023



Fermions on a 3-brane:

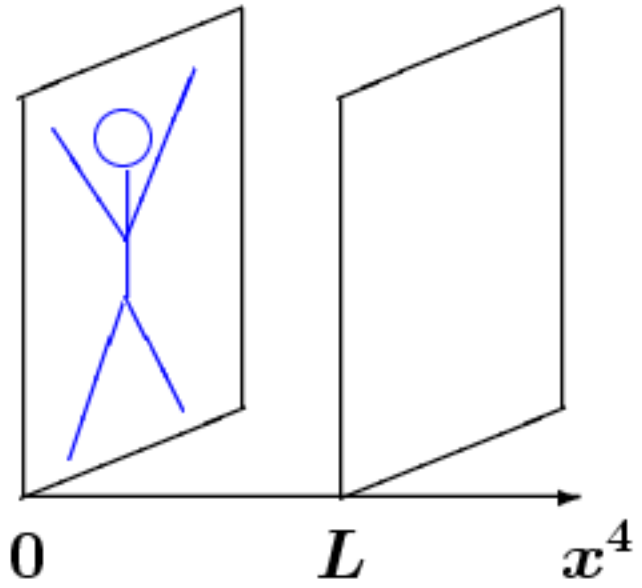


A 4-th universal spatial dimension:



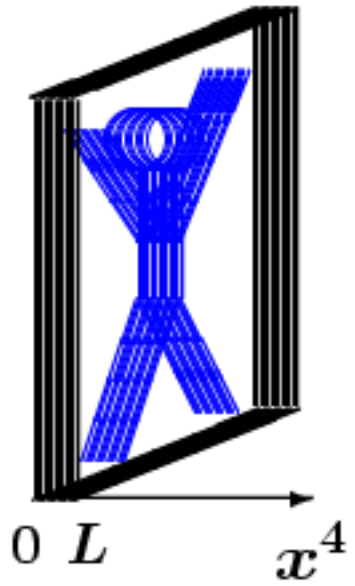
We all have a constant thickness in the 4th spatial dimension.

Fermions on a 3-brane:



A 4-th universal spatial dimension:

UED = Braneless theory



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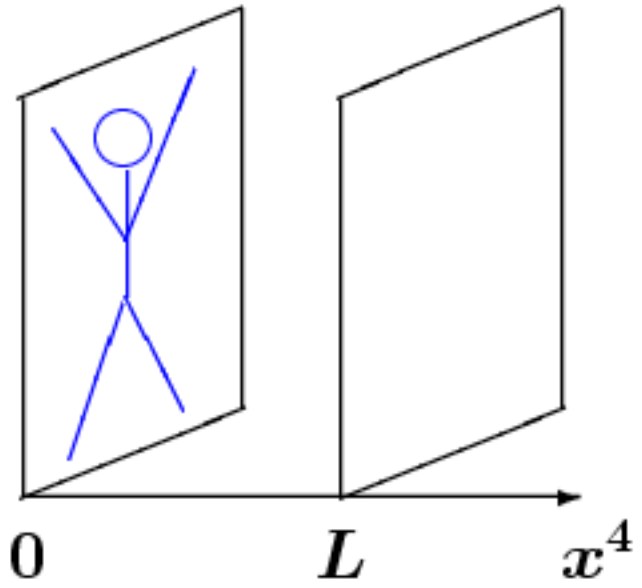
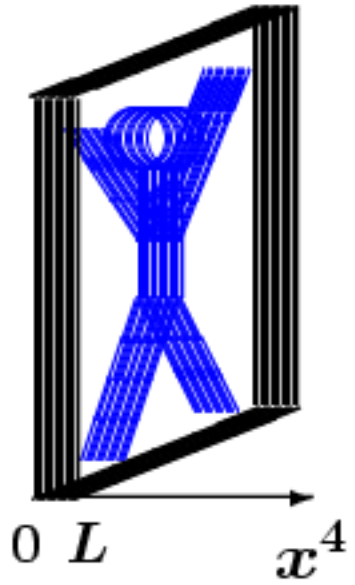
Fermions on a 3-brane:



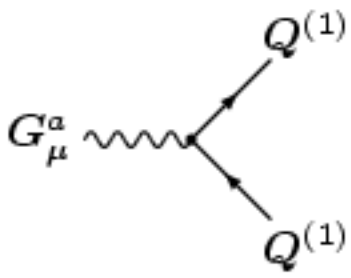
A 4-th universal spatial dimension:

UED = ~~Branes Xtra Dim~~
No-braner theory

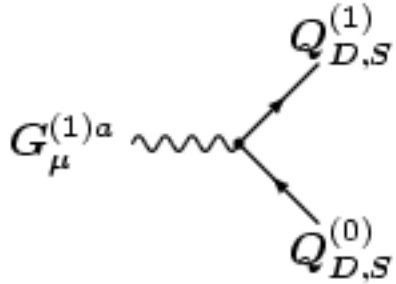


We all have a constant thickness in the 4th spatial dimension.

Feynman rules relevant for QCD production of KK particles at hadron colliders:



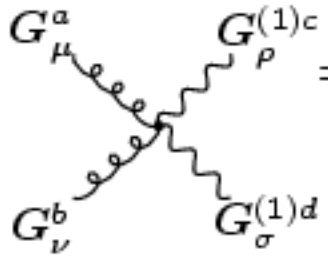
$$= -ig_s\gamma^\mu T^a$$



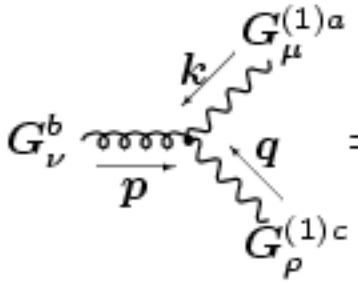
$$= -ig_s\gamma^\mu P_{L,R} T^a$$

Interaction of a level-1 quark with a level-1 gluon is chiral

Feynman rules for interactions of standard-model gluons with KK modes are fixed by gauge invariance:

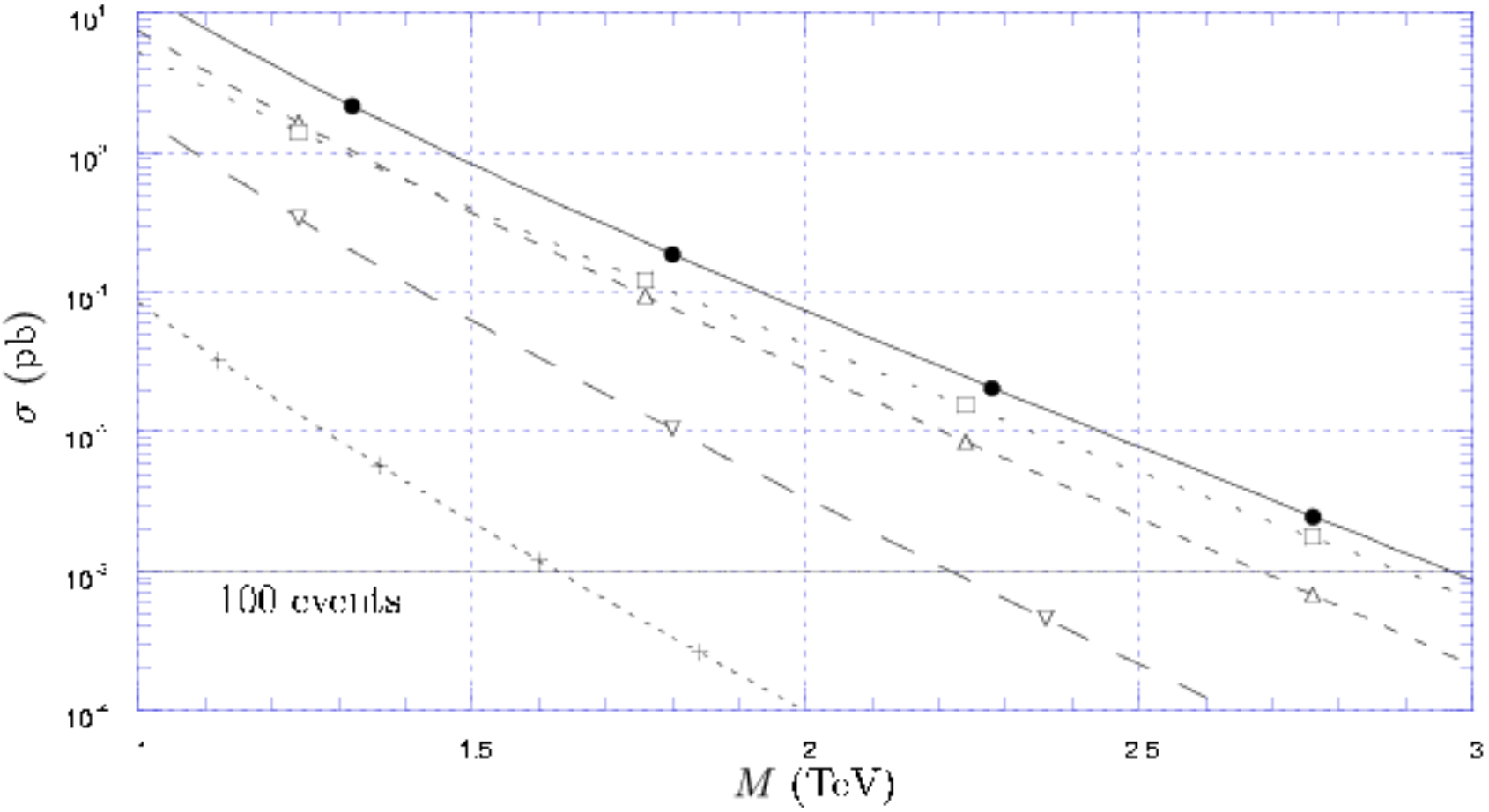


$$= -ig_s^2[f^{abe}f^{cde}(g^{\mu\rho}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\rho}) + f^{ace}f^{bde}(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\sigma}g^{\nu\rho})$$
$$+f^{ade}f^{bce}(g^{\mu\nu}g^{\rho\sigma} - g^{\mu\rho}g^{\nu\sigma})]$$



$$= g_s f^{abc}[(k-p)_\lambda g_{\mu\nu} + (p-q)_\mu g_{\nu\rho} + (q-k)_\nu g_{\mu\rho}]$$

Cross section for production of a pair of level-1 particles at the LHC, as a function of the compactification scale $1/R$:

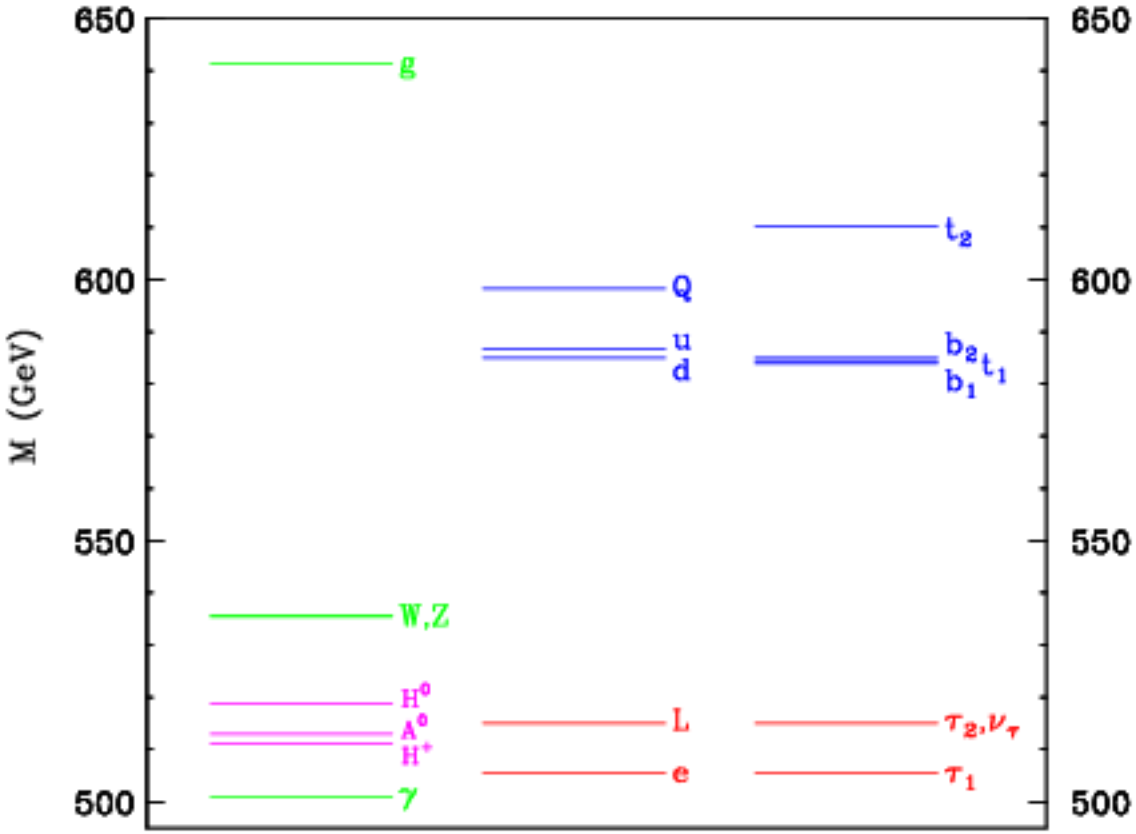


(Macesanu, McMullen, Nandi, hep-ph/0201300)

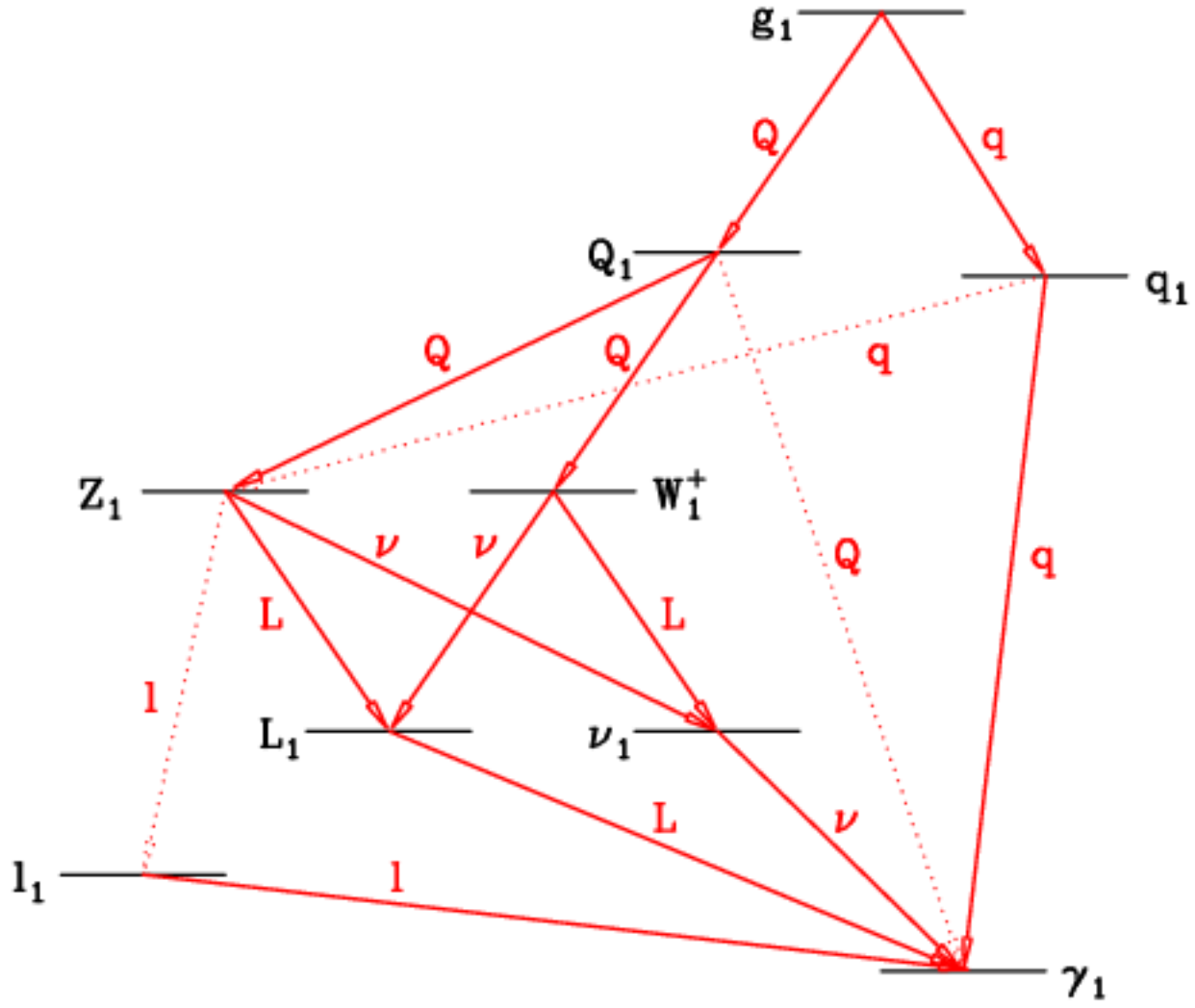
(1) modes have a tree-level mass of $1/R$, and KK parity $-$.

One-loop contributions (and electroweak symmetry breaking) split the spectrum *(Cheng, Matchev, Schmaltz, hep-ph/0204342)*

Mass spectrum of the (1) level:

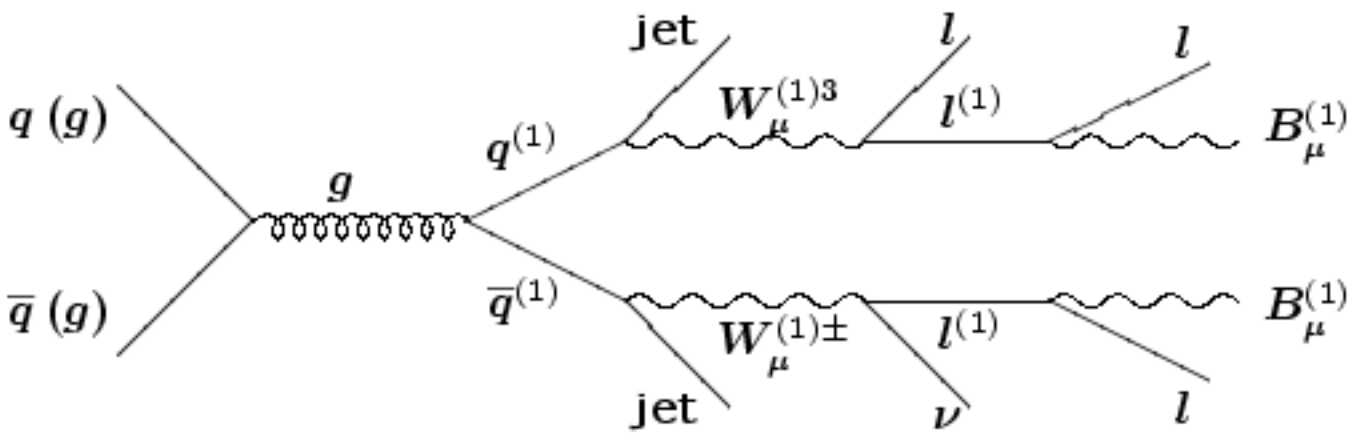


Decay modes of the KK particles:



Homework: compute the branching fractions of the level-1 particles.

Pair production of (1) modes at hadron colliders:



Look for: **2 hard leptons (~ 100 GeV)**

+ 1 soft lepton (~ 10 GeV)

+ 2 jets (~ 50 GeV)

+ $\not{E}_T$

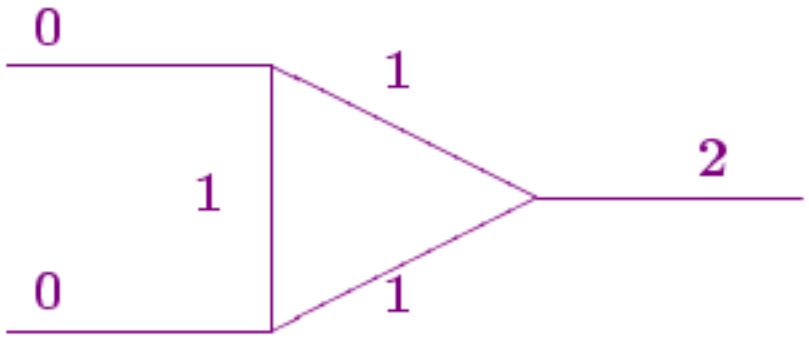
(Cheng, Matchev, Schmaltz, hep-ph/0205314; ...)

Homework: draw other diagrams which contribute to this signal.

CDF analysis of $3l + \not{E}_T$: $1/R > 280$ GeV (Run I)

At one-loop level: $j_1 \pm j_2 \pm ... \pm j_n =$ **even**

At colliders: s**-channel production of the 2-modes**



Kaluza-Klein parity: invariance under reflections with respect to the center of the compact dimension.

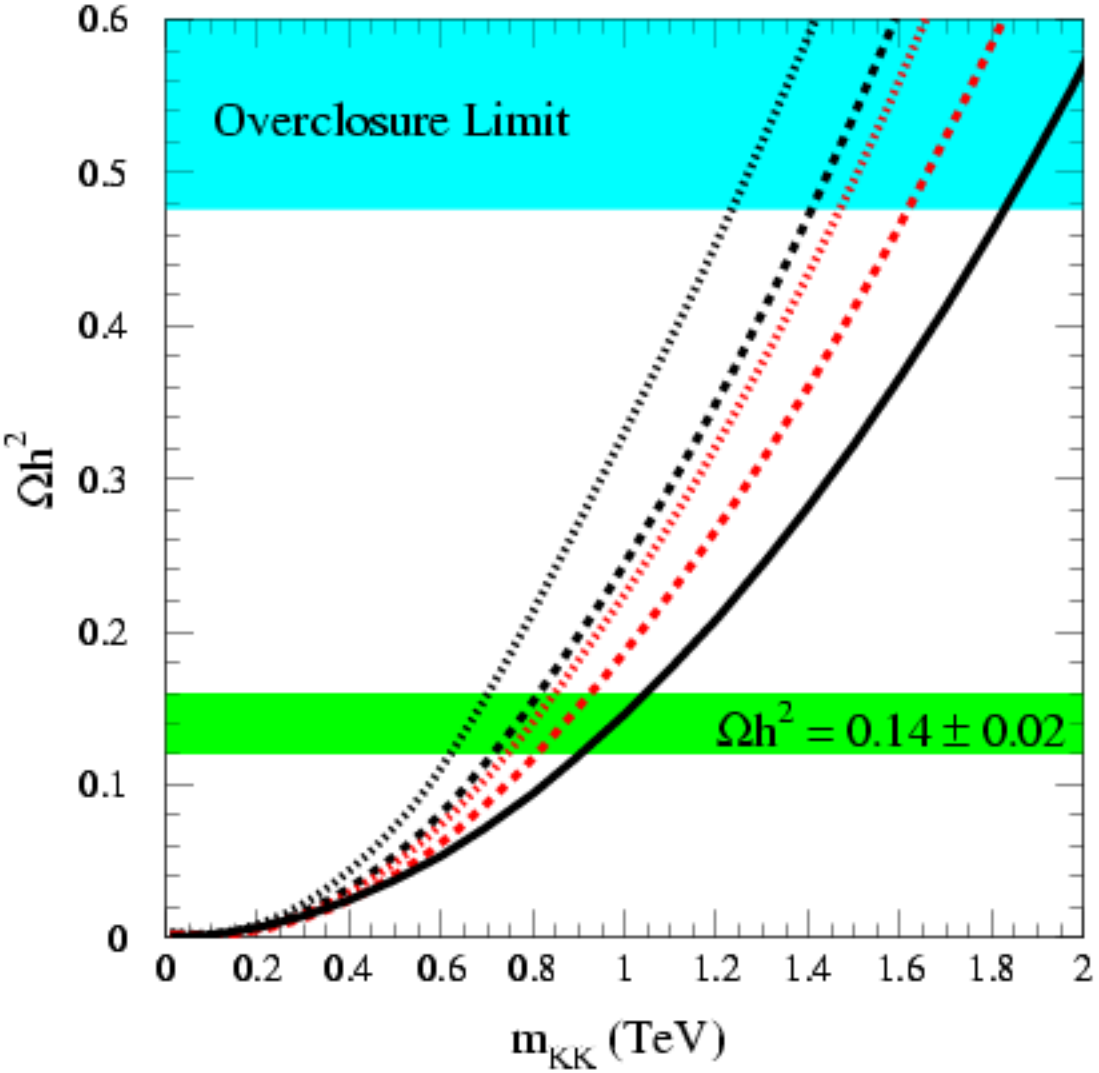
KK parity $(-1)^j$ **is conserved** $\Rightarrow$ **lightest KK-odd particle is stable.**

(only KK modes with odd j *are odd under KK parity)*

Lightest KK particle is stable in UED:

$\gamma^{(1)}$ is a viable dark matter candidate

(from Servant, Tait, hep-ph/0206071)



Importance of discrete symmetries:

Standard model must be extended in order to include dark matter: a new electrically-neutral stable particle.

Stability of dark matter must be ensured by some symmetry.

Simplest possibility: a new discrete symmetry.

Examples:

- **Supersymmetry with R parity**
- **Universal extra dimensions (KK parity)**
- **Little Higgs models with T parity**

Bonus:

If new particles couple only in pairs to standard model ones, then the contributions to electroweak observables are loop-suppressed!

$\Rightarrow$ new particles may be light enough for being discovered soon at colliders!

At the Tevatron and the LHC:

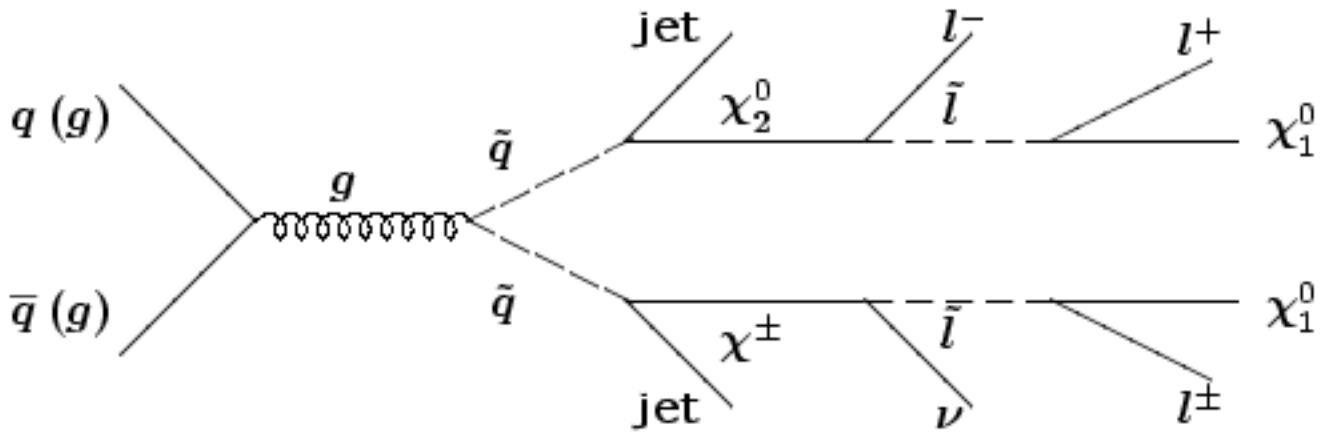
pair production of colored odd particles,

followed by cascade decays through lighter odd particles,

until a pair of dark matter candidates escapes the detector.

$\Rightarrow$ Generic signal: missing E_T + jets + leptons

E.g., squark production and cascade decays to neutralinos:



Look for: **3 leptons + 2 jets + $\not{E}_T$**

Similarity between supersymmetry, little Higgs with KK parity, and one universal extra dimension is not accidental:

- $N = 1$ supersymmetry is an extra dimension with anticommuting coordinate
- Little Higgs with T parity is a deconstructed extra dimension.

An important distinction: spins of partners are different

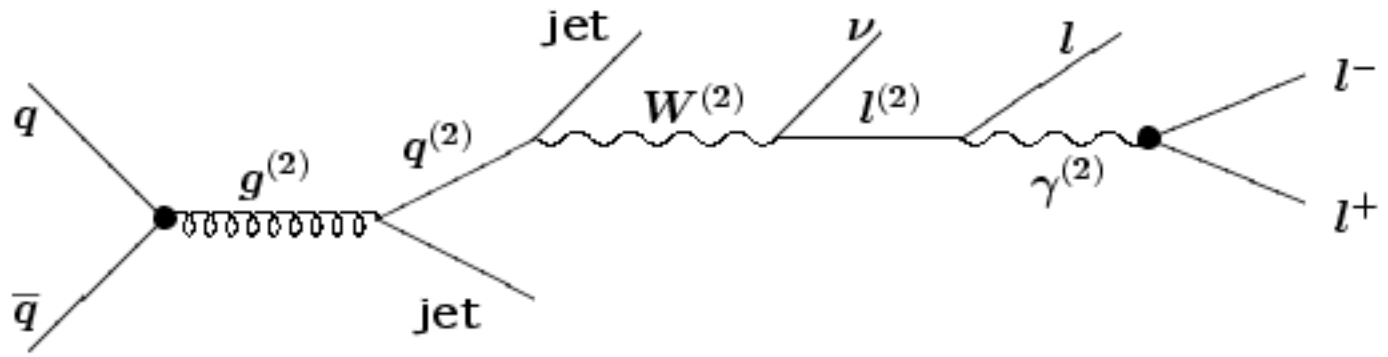
(squarks have spin 0, KK quarks have spin 1, etc.)

Measuring spins at the LHC is challenging but not impossible.

One Universal Extra Dimension has a distinctive feature:

Second-level masses: $\sim 2/R$.

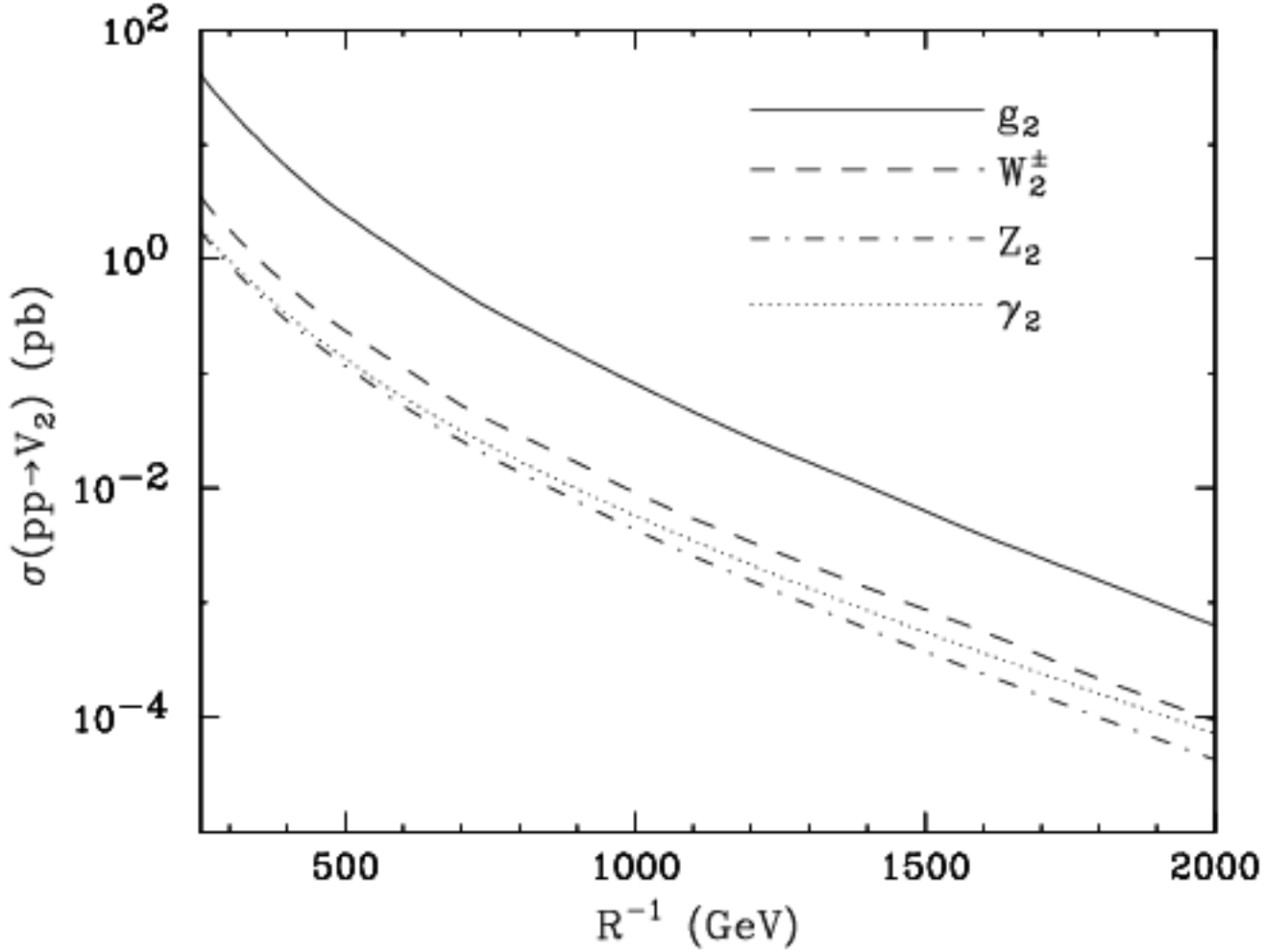
Cascade decay of the 2-mode is followed by $\gamma^{(2)}$ **decay into hard leptons:**



Particularly useful at the LHC (A. Datta, K. Kong, K. Matchev, hep-ph/0509246)

$\longrightarrow$ *would allow discrimination of UED & MSSM.*

Cross section for s-channel production of a level-2 boson (of mass $2/R$ + corrections) at the LHC:



(A. Datta, K. Kong, K. Matchev, hep-ph/0509246)

Conclusions

- One Universal Extra Dimension
  - compactification scale can be as low as ~ 300 GeV.
  - lightest KK mode is a dark matter candidate

- Look for Kaluza-Klein modes at the Tevatron and the LHC:
  - 3 soft leptons + jets + $\not\!\!E_T$
  - series of narrow $\ell^+\ell^-$ resonances due to level-2 particles.