Two Universal Extra Dimensions

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If some SM fields propagate in the bulk $\Rightarrow \frac{1}{R} \gtrsim 1\ TeV$.

But if we assume all fields can propagate in the extra dimensions. What is the allowed $R$?

$p_5$ conservation in the bulk $\Rightarrow$ KK number conservation.

Orbifolding breaks KK number $\rightarrow$ KK parity (LKP is stable)
UED Phenomenology

Electroweak precision constraints:

\[
\frac{1}{R} \gtrsim 300 \text{ GeV for 5D} \\
\frac{1}{R} \gtrsim (400 - 600) \text{ GeV for 6D}
\]

Current direct searches give similar bounds.

But, almost degenerate KK levels \( \Rightarrow \) little energy release. (Cheng, Matchev, Schmaltz '02).

Phenomenology of 1 UED with level 2 KK modes (Datta, Kong, Matchev)
Two Universal Extra Dimensions

**Motivation:**
- Possible to avoid proton decay (Appelquist, Dobrescu, Ponton)
- To cancel anomalies $\Rightarrow$ 3 generations (Dobrescu, Poppitz).
- Explore different phenomenology
The Chiral Square

⇒ chiral fermions in the 4D effective theory.
TED: KK Modes

- KK Expansion:

\[ \Phi = \frac{1}{\pi R} \sum_{j,k} \Phi^{(j,k)}(x) \left( \cos \frac{jx^4 + kx^5}{R} + \cos \frac{kx^4 - jx^5}{R} \right) \]

- Masses:

\[ M_{j,k} = \frac{1}{R} \sqrt{j^2 + k^2} = 0, 1/R, \sqrt{2}/R, 2/R, \cdots \]

- Presence of the non-eaten GB. For each gauge boson in 6D, a scalar in the spectrum: \( G_H, W_H, B_H \).

- 6D Gauge bosons:
  - Tower of spin-1
  - Tower of spin-0 (eaten)
  - Tower of spin-0 (in the spectrum)
Localized Operators

Fixed points in the conical singularities:

- At $(0, 0)$, $(\pi R, \pi R)$ and $(0, \pi R)$
- Bulk interactions invariant under reflections w.r.t. center of square

$\Rightarrow Z^K_2$, KK parity: Operators at $(0, 0)$ same as ops. at $(\pi R, \pi R)$

$$
\int_0^{\pi R} dx^4 \int_0^{\pi R} dx^5 \{ \mathcal{L}_{\text{bulk}} + \delta(x_4)\delta(\pi R - x_5)\mathcal{L}_2 \\
+ [\delta(x_4)\delta(x_5) + \delta(\pi R - x_4)\delta(\pi R - x_5)]\mathcal{L}_1 \}
$$

- But, physics above cut-off can also induce localized operators. Assume this respects $Z^{kk}_2$

$\Rightarrow$ KK parity is preserved $\Rightarrow$ LKPs
Localized Operators

Operators: Fermion and gauge kinetic terms. E.g.

\[ \frac{C_{pU}}{\Lambda^2} i \bar{U}_R \Gamma^\mu D_{\mu} U_R + \left( \frac{C'_{pU}}{\Lambda^2} i \bar{U}_R \Gamma^l D_l U_L + \text{H.c.} \right), \]

\[ - \frac{1}{4} \frac{C_{pG}}{\Lambda^2} G_{\mu\nu} G_{\mu\nu} - \frac{1}{2} \frac{C'_{pG}}{\Lambda^2} (G_{45})^2 \]

Will induce:
- Mass splitting in the KK spectrum
- KK-number violating couplings
Localized Operators

From:

UV physics above the cut-off. NDA estimate

\[ \Lambda^2 \frac{N_c g_6^2}{\ell_6} \approx 1 \Rightarrow \Lambda R \approx \left( \frac{32}{N_c \alpha_s} \right)^{1/2} \approx 10 \]

Also

\[ C' s \sim \frac{\ell_6}{\ell_4} \sim 8\pi \]

⇒ Effective 4D coupling is

\[ \sim \frac{g_s^2 N_c}{16\pi^2} \]
Localized Operators

Also contributions from below $\Lambda$. E.g. at one-loop, for one of the fermion couplings

$$\frac{C_{1f}}{(\pi \Lambda R)^2} = \left[ -4 \sum_A g_A^2 C_2(f) + \frac{5}{8} \sum_i \lambda_i^2 \right] \frac{1}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2}$$

For one of the gauge couplings

$$\frac{C_{1A}}{(\pi \Lambda R)^2} = \left[ -\frac{14}{3} C_2(A) + \frac{2}{3} \sum_f T(f) + \frac{5}{12} \sum_s T(s) \right]$$

$$\times \frac{g_A^2}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2},$$

(1)

Log enhanced w.r.t. the bare contributions.
The \((1, 0)\) level spectrum:

\[ G_{\mu}^{(1, 0)} \]

\[ W_{\mu}^{(1, 0)} \]

\[ B_{\mu}^{(1, 0)} \]

\[ Q_{+}^{(1, 0)} \]

\[ Q_{-}^{(1, 0)} \]

\[ U_{-}^{(1, 0)} \]

\[ T_{-}^{(1, 0)} \]

\[ D_{-}^{(1, 0)} \]

\[ H_{1, 0} \]

\[ G_{H}^{(1, 0)} \]

\[ L_{-}^{(1, 0)} \]

\[ E_{-}^{(1, 0)} \]

\[ B_{H}^{(1, 0)} \]

\( B_{H} \) is the LKP \( \Rightarrow \) spin-0 Dark Matter

\( 1/R = 500 \text{ GeV} \)
Kaluza-Klein Spectrum Level 2

The $(1, 1)$ level spectrum:

![Graph showing the mass spectrum with various particles marked at different masses.](image-url)
**KK-number Violating Interactions**

Bulk loops → localized KK-number violation:

- KK gluon with zero-mode quarks

\[ g_s C_{j,k}^{qG} \left( \overline{q} \gamma^\mu T^a q \right) G_{\mu}^{(j,k)a} , \]

- The spinless adjoint \( G_H \) couples through the operator

\[ \frac{g_s \tilde{C}_{j,k}^{qG}}{M_{j,k}} \left( \overline{q} \gamma^\mu T^a q \right) D_{\mu} G_{H}^{(j,k)a} , \]

\( G_H, W_H \) and \( B_H \) coupling proportional to \( m_f \).

\[ \Rightarrow Br(X_H \rightarrow t\bar{t}) \simeq 100\% \]
1st KK level \((1, 0)\) must be pair produced

2nd KK level \((1, 1)\) can be in s-channel:

- \(q \bar{q} \rightarrow G^{(1,1)}_{\mu}\)
- \(q \bar{q} \rightarrow W^{3(1,1)}_{\mu}\)
- \(q \bar{q} \rightarrow B^{(1,1)}_{\mu}\)
S-Channel $(1, 1)$ gauge boson production at the Tevatron

\[ \sigma(p\bar{p} \rightarrow V_{(1,1)}^{\mu}) \ [\text{fb}] \]

\[ M_{V_{(1,1)}} \ [\text{GeV}] \]
S-Channel $(1, 1)$ gauge boson production at the LHC
TED Phenomenology

But, decays of $W^{3(1,1)}_\mu$ and $B^{(1,1)}_\mu$ dominated by $q\bar{q}$ final states (originated by QCD-dominated loops).

$\Rightarrow$ EW KK modes are Leptophobic
S-channel production of the $G_{\mu}^{(1,1)}$. 

![Diagram of S-channel production of $G_{\mu}^{(1,1)}$.]
TED Phenomenology

Production and Decay of $W^{(1,1)}_{\mu}$ and $B^{(1,1)}_{\mu}$

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5 Resonances in the $t\bar{t}$ spectrum ($G^{(1,1)}_\mu \rightarrow t\bar{t}$ small)

But only 3 will be resolved:

- $G^{(1,1)}_H + W^{3(1,1)}_\mu : \sim 1.10 \ M_{1,1}$
- $B^{(1,1)}_\mu + W^{3(1,1)}_H : \sim 0.97 \ M_{1,1}$
- $B^{(1,1)}_H : \sim 0.86 \ M_{1,1}$

and $M_{1,1} = \sqrt{2}/R$. 
Production of $t\bar{t}$ resonances at the Tevatron

$\sigma (p\bar{p} \rightarrow V^{(1,1)} \rightarrow t\bar{t})$ [fb]

$M(t\bar{t})$ [GeV]
$t\bar{t}$ Resonances - Tevatron

Sum of $t\bar{t}$ pairs from all resonances at the Tevatron
$t\bar{t}$ Resonances - LHC

![Graph showing the relationship between $M_{tt}$ and the production cross-section $\sigma(\text{pp} \rightarrow V_{\mu}^{(1,1)})$ in fb.]
Conclusions

- Two Universal Extra Dimensions is a well-motivated/distinct scenario
- Crucial differences with 1 UED:
  - Spinless adjoints $X_H$, with $Br(X_H \rightarrow \bar{t}t) \approx 100\%$
  - $B_H$ is the LKP
  - $M_{1,1} = \sqrt{2}/R$: $\Rightarrow$ 2-level $\rightarrow$ 1st level pair is strictly forbidden.
  - $t\bar{t}$ rich signals at the Tevatron and LHC
- Very different phenomenology
- Generic: We can see leptophobic, weakly coupled resonances at hadron colliders
- SM in UEDs not natural. But basic features of analysis will remain