Universal Extra Dimensions: Symmetries and Signatures

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Universal Extra Dimensions

All SM particles propagate in the same D-dimensional space
(there may be additional "sterile" dimensions, accessible to SM singlets)

In compactifications without orbifold singularities $\longrightarrow$ conservation of extra dimensional momentum

- KK modes cannot be singly produced, and affect low-energy 4D effective theory at loop level

$$1/R \gtrsim \text{ few hundred GeV}$$

- Lightest KK particle is stable

Chiral 4D effective theory generally introduces singularities (chirality from boundary conditions)

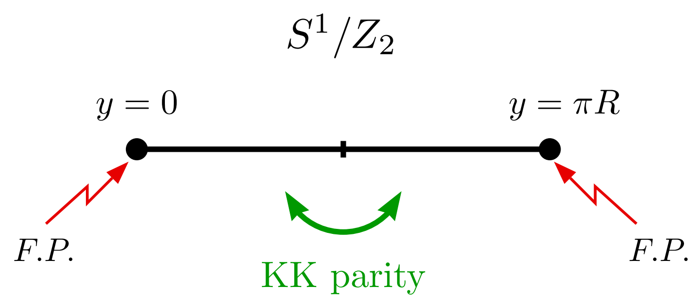
$\rightarrow$ KK number is broken, but discrete KK parity naturally survives

5D case has been studied extensively: EW constraints, dark matter, collider phenomenology, flavor violation signals, . . .

Bulk: SM interactions

On boundaries: additional operators

In fact, bulk interactions generate brane localized log divergences



$\boxed{\text{Minimal model: localized operators vanish at a “high” scale } \Lambda}$

• Predictivity: low-energy contribution ($1/R < \mu < \Lambda$) is calculable

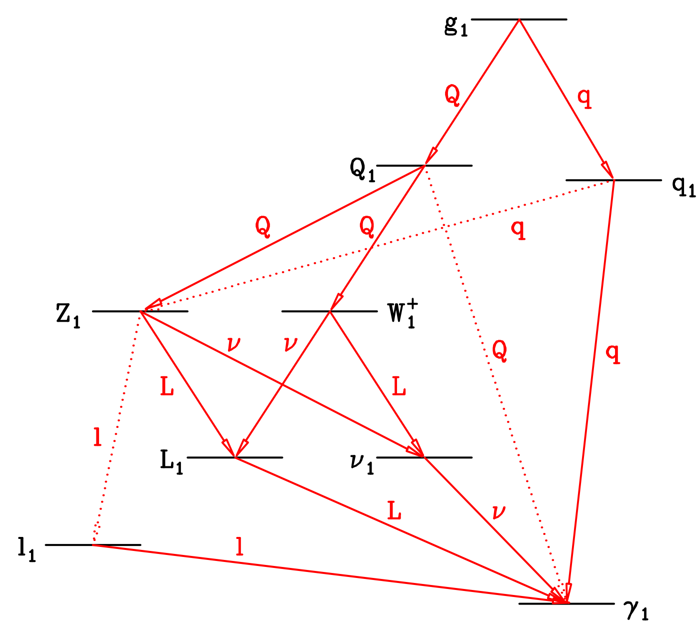
• Physics of lowest lying KK modes largely determined by the localized operators at a scale $\mu \sim 1/R$

• Highly degenerate spectrum: missing energy plus soft stuff

$\longrightarrow$ challenging for hadron machines

$\longrightarrow$ KK bound states at NLC

(see next talk by M. Sher)



(Cheng, Matchev, Schmaltz)

The Six-Dimensional Case

6D theories have a richer structure than 5D ones:

- Spacetime symmetries: rotations in the transverse space
  $\rightarrow$ discrete subgroups may survive compactification and constrain low-energy physics in interesting ways

- Bulk fermions and gauge interactions: 6D anomalies
  – purely gravitational anomalies $\rightarrow$ three right-handed neutrinos
  – SU(2) global anomaly $\rightarrow N_g = 0 \bmod 3$

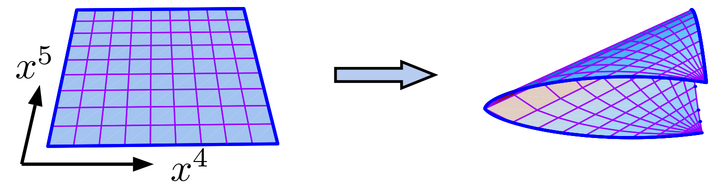
I will consider the 6D UED model in some detail

Work in collaboration with B. Dobrescu and G. Burdman

Compactification on the Folded Square

Dobrescu & EP (2004)

Identify adjacent sides of a square:



Consider a free scalar field theory

$$S_\Phi = \int d^4x \int_0^L dx^4 \int_0^L dx^5 \left(\partial_\alpha \Phi^\dagger \partial^\alpha \Phi - M_0^2 \Phi^\dagger \Phi\right)$$

Previous identifications correspond to imposing

$$\Phi(x^\mu, y, 0) = e^{i\theta} \Phi(x^\mu, 0, y) \qquad \Phi(x^\mu, y, L) = e^{i\tilde{\theta}} \Phi(x^\mu, L, y)$$

and the variational principle further requires

$$\partial_5 \Phi|_{(x^4,x^5)=(y,0)} = -e^{i\theta}\ \partial_4 \Phi|_{(x^4,x^5)=(0,y)}$$

$$\partial_5 \Phi|_{(x^4,x^5)=(y,L)} = -e^{i\tilde{\theta}}\ \partial_4 \Phi|_{(x^4,x^5)=(L,y)}$$

Working in momentum space we can write

$$\Phi(x^\mu, x^4, x^5) = \frac{1}{L}\sum_{j,k} \Phi^{(j,k)}(x^\mu) f^{(j,k)}(x^4, x^5)$$

where the Kaluza-Klein wavefunctions satisfy

$$\left(\partial_4^2 + \partial_5^2 + M_{j,k}^2\right) f^{(j,k)}(x^4, x^5) = 0 \qquad M_{j,k}^2 = \frac{j^2 + k^2}{R^2}$$

Nontrivial solutions to the Klein-Gordon equation exist only when

$$\theta = n\frac{\pi}{4} \qquad n = 0, 1, 2, 3$$

and either

$$\begin{aligned} e^{i\tilde{\theta}} &= e^{i\theta} \quad \text{with} \quad j, k \in \mathbf{Z} \qquad \text{or} \\ e^{i\tilde{\theta}} &= -e^{i\theta} \quad \text{with} \quad j + \frac{1}{2}\,,\; k + \frac{1}{2} \in \mathbf{Z} \end{aligned}$$

$$f_n^{(j,k)}(x^4, x^5) = \left[e^{-in\pi/2}\cos\pi\left(\frac{jx^4 + kx^5}{L} + \frac{n}{2}\right) + \cos\pi\left(\frac{kx^4 - jx^5}{L} + \frac{n}{2}\right)\right]$$

Generic properties:

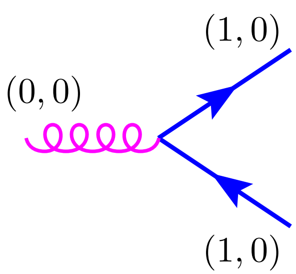
- Four "types" of fields labeled by $n = 0, 1, 2, 3$. Only $n = 0$ has a zero mode $\longrightarrow$ SM fields

- Mass eigenstates are linear superpositions of waves going back and forth, along x^4 and x^5 directions

  $\longrightarrow$ Tree-level "conservation law"

$$(j_1, k_1) + (j_2, k_2) + \cdots + (j_r, k_r) \longrightarrow (P_4, P_5)$$

$$\text{if} \quad \mathrm{P}_4 = \sum_{\mathrm{i}} \pm \mathrm{p_i} \quad \text{with} \quad \mathrm{p} = (\mathrm{j} \;\; \text{or} \;\; \mathrm{k})$$



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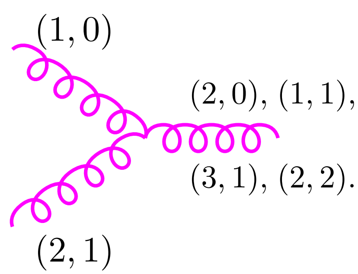

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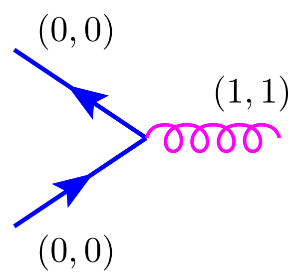
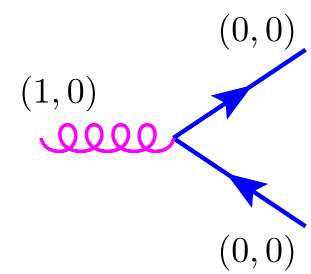


Not allowed

(allowed at loop level)



Not allowed

Fermions in Six Dimensions

In 6D we may define (four component) spinors of definite 6D chirality

$$\Psi_+ = \chi_{+_R} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \chi_{+_L} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\Psi_- = \chi_{-_L} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \chi_{-_R} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\Gamma^\mu = \gamma^\mu \otimes \mathbf{1}_{2\times 2}$$
$$\Gamma^5 = \gamma^5 \otimes \sigma^2$$
$$\Gamma^4 = \gamma^5 \otimes \sigma^1$$
$$\Gamma^7 = \gamma^5 \otimes \sigma^3$$

Each 4D chiral component can be decomposed as

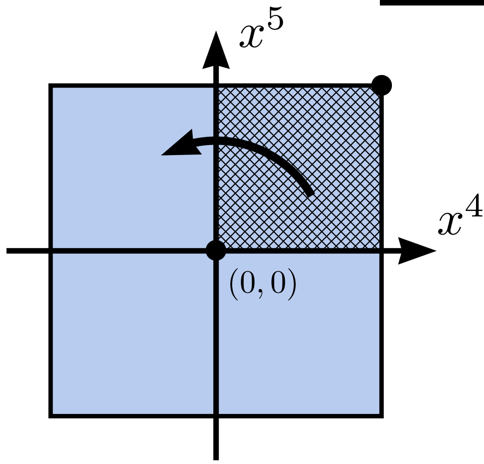
$$\chi_{L,R}(x^\mu, x^4, x^5) = \frac{1}{L} \sum_{j,k} \chi^{(j,k)}_{L,R}(x^\mu) f^{(j,k)}_{n_{L,R}}(x^4, x^5)$$

with the left- and right-handed wavefunctions satisfying

$$n^+_L = n^+_R + 1 \bmod 4 \qquad n^-_L = n^-_R - 1 \bmod 4$$

We assign $n = 0$ to Q_{+L}, U_{-R}, D_{-R}, $L_{\pm L}$, $E_{\mp R}$, $N_{\mp R}$

Symmetries of the KK Theory



Under transverse rotations by $\pi/2$ about $(0,0)$

$$(\chi_{+_R}, \chi_{-_L})|_{(x^4,x^5)} \quad \mapsto \quad e^{\frac{i}{2}(\frac{\pi}{2})} \, (\chi_{+_R}, \chi_{-_L})|_{(-x^5,x^4)}$$

$$(\chi_{+_L}, \chi_{-_R})|_{(x^4,x^5)} \quad \mapsto \quad e^{-\frac{i}{2}(\frac{\pi}{2})} \, (\chi_{+_L}, \chi_{-_R})|_{(-x^5,x^4)}$$

The KK wavefunctions satisfy $f_n^{(j,k)}(-x^5, x^4) = e^{-in\pi/2} f_n^{(j,k)}(x^4, x^5)$:

$$\Psi_{\pm L}(x^4, x^5) \quad \mapsto \quad e^{-i(n \mp \frac{1}{2})(\frac{\pi}{2})} \Psi_{\pm L}(x^4, x^5)$$

which corresponds to a Z_8 (internal) symmetry of the compactified theory

For the SM : $\qquad \mathcal{Q} \longrightarrow \mathrm{e}^{\mathrm{i}\pi/4} \mathcal{Q} \qquad \mathcal{L} \longrightarrow \mathrm{e}^{\pm \mathrm{i}\pi/4} \mathcal{L}$

Operators containing only SM fields (0-modes) satisfy the selection rule

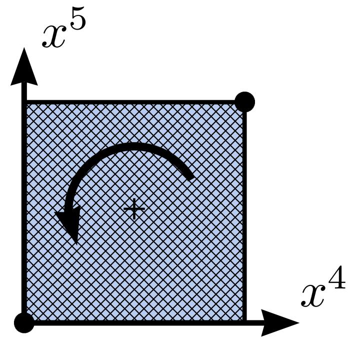
$$3\Delta B \pm \Delta L = 0 \text{ mod } 8$$

$\longrightarrow$ Proton decay is suppressed, neutrinos are Dirac

Also: if $A_{4,5}^{(1,0)}$ lightest among $n \neq 0$ states $\longrightarrow$ stable!

Stable Kaluza-Klein Modes

Consider rotations by 180° about the *center* of the square



This gives rise to a "Kaluza-Klein parity"

$$f_n^{(j,k)}(L - x^4, L - x^5) \quad = \quad (-1)^{j+k+n} f_n^{(j,k)}(x^4, x^5)$$

$$\Longrightarrow \quad \Phi^{(j,k)} \quad \mapsto \quad (-1)^{j+k}\Phi^{(j,k)}$$

The KK parity is preserved provided the localized operators at $(0, 0)$ and (L, L) are the same.

It follows that the lightest Kaluza-Klein particle (LKP), labeled by $(j, k) = (1, 0)$, is naturally stable.

It is likely that the LKP is $\gamma^{(1,0)}$ $\rightarrow$ excellent dark matter candidate

(Servant and Tait)

Comment: in 5D, KK parity associated to inversion in x^5. In 6D, associated with the proper 6D Lorentz group.

Gauge Bosons and Scalars

Gauge fixing: $\mathcal{L}_{GF} = -\frac{1}{2\xi}(\partial_\mu A^\mu - \xi\partial_4 A_4 - \xi\partial_5 A_5)^2$, leads to

$$A_\mu \to n = 0 \qquad A_\mp = A_4 \mp iA_5 \to n = 1, 3$$

and decouples the degrees of freedom:

$$S = \sum_{(j,k)} \int d^4x \left\{ -\frac{1}{4} F^{(j,k)}_{\mu\nu} F^{(j,k)\mu\nu} + \frac{1}{2} M^2_{j,k} [A^{(j,k)}_\mu]^2 - \frac{1}{2\xi} [\partial^\mu A^{(j,k)}_\mu]^2 \right.$$
$$\left. + \frac{1}{2}[\partial_\mu h^{(j,k)}]^2 - \frac{1}{2} M^2_{j,k} [h^{(j,k)}]^2 + \frac{1}{2}[\partial_\mu \phi^{(j,k)}]^2 - \frac{1}{2}\xi M^2_{j,k}[\phi^{(j,k)}]^2 \right\}$$

where

$$h^{(j,k)} = \frac{1}{\sqrt{j^2+k^2}}(kA_4^{(j,k)} - jA_5^{(j,k)}) \sim F_{45}$$
$$\phi^{(j,k)} = \frac{1}{\sqrt{j^2+k^2}}(jA_4^{(j,k)} + kA_5^{(j,k)})$$

Collider signatures

As in 5D, the mass degeneracy is broken by localized operators, at $(0,0)$, $(0,L)$ and (L,L), which receive contributions from the UV theory as well as from the KK modes below Λ.

It is natural to assume that such operators are of order one loop

Physics of first level KK modes very similar to 5D: pair production followed by cascade decays into the LKP
$\rightarrow$ missing energy plus soft jets and/or leptons

It is interesting to consider the second level with masses $\sim M_{(1,1)} = \frac{\sqrt{2}}{R}$

Production:

- pair produced if there is enough energy
- singly produced, though with smaller probability (through localized terms)

At hadron machines, $g^{(1,1)}$ more readily produced. It cascade decays to the lightest second level KK mode.

Decays into $(1, 0)$ states are kinematically closed $\rightarrow$ lightest second mode decays into SM particles

L2KP decay proceeds through localized operators $\rightarrow$ narrow resonance

In a "minimal" version of the present model, with localized kinetic terms dominated by radiative corrections in the 6D theory, the lightest second KK particle is the $\gamma^{(1,1)} \simeq B^{(1,1)}$

Can look for

$$\gamma_\mu^{(1,1)} \rightarrow l^+ l^-$$

Reach at the Tevatron and LHC: work in progress ...
(Burdman, Dobrescu, and E.P.)

Conclusions

- UED's provide an attractive scenario for physics beyond the SM
- The 6D case has a number of interesting properties
  - Number of generations $N_g = 0 \bmod 3$
  - Long proton lifetime, even with baryon number violation at the TeV scale. Also, no N-$\bar{N}$ oscillations
  - Neutrino phenomenology: neutrinos are Dirac, no $0\nu\beta\beta$ decay
  - Stable massive particles provide a good dark matter candidate
  - Present bounds on $1/R \gtrsim 300 - 400$ GeV
  - Good chance for discovery in the dilepton channel. Not necessarily missing energy signature