New dark matter candidates in non-minimal UED

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(work in progress)

Outline

- Review of universal extra dimensions
- UED as an effective field theory
- Changing the lightest Kaluza-Klein particle via boundary localized terms
- Conclusions

UED review

- Consider a 5D model in which *all* fields propagate in a flat extra dimension. [Appelquist, Cheng, Dobrescu, PRD **64**: 035002 (2001)]
- Identify the zero mode spectrum with the SM.
- Compactification on S^1/Z_2 ($y \in [0, \pi R]$) allows for chiral fermion zero modes.
- Kaluza-Klein number conservation is broken by the orbifolding, but for a S^1/Z_2 compactification, a Z_2 parity ("KK-parity") remains.
  - KK excitations can only be produced pairwise.
  - stable lightest KK particle ("LKP") $\rightarrow$ Dark Matter
- In the most commonly considered UED model (MUED), the LKP is the $B^{(1)}$.

UED review

The UED action:

$$S_{UED,bulk} = S_g + S_H + S_f$$

with

$$\begin{aligned} S_g &= \int d^5x - \frac{1}{4\hat{g}_3^2} G^A_{MN} G^{AMN} - \frac{1}{4\hat{g}_2^2} W^I_{MN} W^{IMN} - \frac{1}{4\hat{g}_Y^2} B_{MN} B^{M} \\ S_H &= \int d^5x (D_M H)^\dagger (D^M H) + \hat{\mu}^2 H^\dagger H - \hat{\lambda}(H^\dagger H)^2 \\ S_f &= \int d^5x\, i\overline{\psi}\gamma^M D_M \psi + \Big(\hat{\lambda}_E \overline{L} E H + \hat{\lambda}_U \overline{Q} U \tilde{H} + \hat{\lambda}_D \overline{Q} D H + \text{h.c} \end{aligned}$$

UED review

- All fields can be expanded in the *same* Kaluza-Klein basis f_n

$$\Phi(x,y) = \sum_n \Phi^{(n)}(x) f_n(y)$$

- By canonically normalizing the zero modes, all 5D couplings are related to the Standard Model couplings by rescaling with the appropriate powers of πR.
- At tree level, UED has two undetermined parameters: The Higgs mass m_h
  and the compactification scale $M_{kk} \equiv R^{-1}$.

UED as an effective field theory

- UED is a five dimensional model $\rightarrow$ non-renormalizable.
- It should be considered as an effective field theory with a cutoff Λ.
- NDA result: $\Lambda \sim 50/R$. *This cutoff is low!*
- Without knowledge of the underlying theory, *all* operators allowed by all symmetries should be considered.
- This includes:
  - higher dimensional operators
  - boundary localized operators allowed by the 4D effective gauge symmetries. Eg:

$$S_{tot} \supset d^5x \frac{r_W}{4} W_{\mu\nu} W^{\mu\nu} \left(\delta(y) + \delta(y - \pi R)\right)$$

UED as an EFT

- The well-studied example: “Minimal” UED

  [Cheng, Matchev, Schmaltz, PRD **66** (2002) 036005]
- In compactifications on S^1/Z_2, loop corrections induce boundary localized kinetic terms.
- Definition of MUED: Assume that *all* boundary localized terms vanish at the cutoff Λ.
- Still, the boundary localized terms are induced at lower scale due renormalization group evolution.

Changing the LKP via boundary localized terms

The central questions:

- *How do non-minimal terms in UED affect the mass spectrum and couplings?*
- *What are the implications for collider phenomenology and dark matter?*

Changing the LKP via boundary localized terms

We consider boundary localized kinetic terms (BLKTs) for the gauge fields and study their effect on the LKP.

$$S_{tot} \supset d^5x \frac{r_i}{4} F^I_{\mu\nu} F^{I,\mu\nu} \left(\delta(y) + \delta(y - \pi R)\right)$$

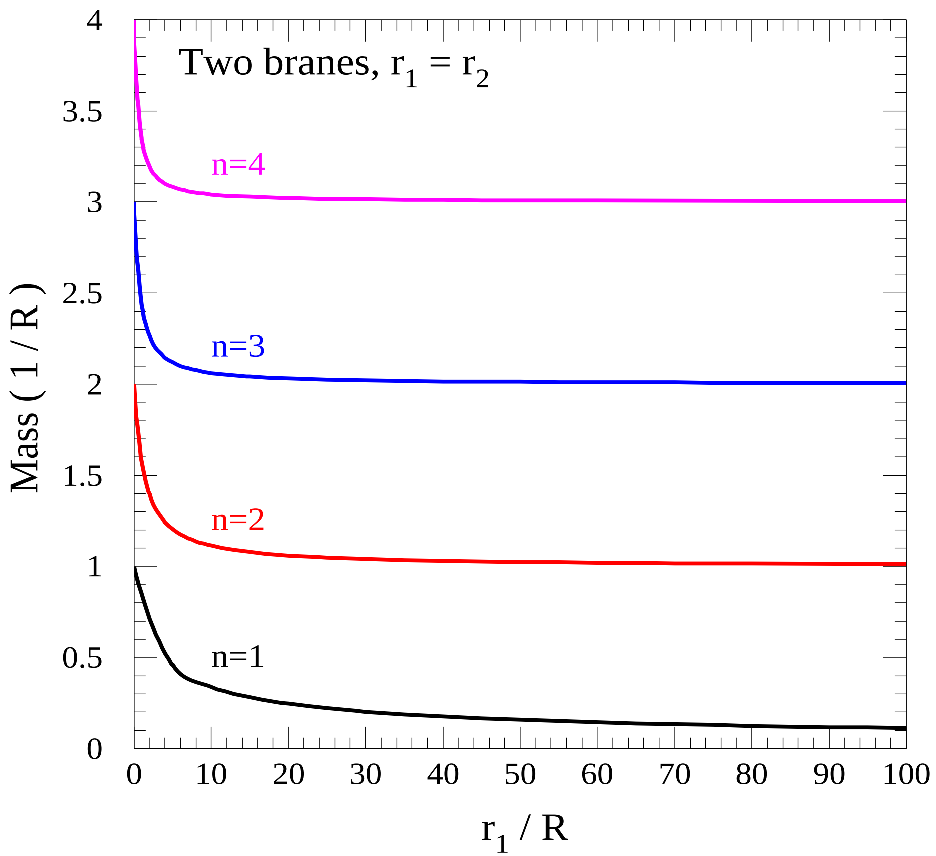
- NDA: $r_i \sim 6\pi/\Lambda R$.
- BLKTs induce mixing between the KK modes.
- [Carena, Tait, Wagner **Acta Phys.Polon.B33:2355,2002**]
  In a pure gauge theory, the mixing can be accounted for by modifying the KK orthogonality relations to

$$\frac{1}{\hat{g}^2} \int dy \left[1 + r\left(\delta(y) + \delta(y - \pi R)\right)\right] f_n(y) f_m(y) = Z_n \delta_{nm}$$

Changing the LKP via boundary localized terms

from [Carena, Tait, Wagner **Acta Phys.Polon.B33:2355,2002]**

The masses of the KK mass eigenmodes $m_{w^{(n)},b^{(n)},g^{(n)}}$ get reduced by the presence of the BLKT.



Changing the LKP via boundary localized terms

Consequences in a full UED setup:

- The Kaluza-Klein basis of the BLKT modified gauge field *differs* from the standard KK basis.
- Implications for an $SU(3)$ BLKT are simple. The $g^{(1)}$ mass gets reduced and can be pushed down to provide the LKP
  $\rightarrow$ phenomenologically very problematic (SIMP Dark Matter).
- EWSB is more complicated as the B, W, and H KK basis now all differ.
- (Technical problem: Gauge-fixing becomes more complicated.)

Changing the LKP via boundary localized terms

When working in unitary gauge, the physical gauge- and Higgs KK modes can be identified (to appear soon). Results:

- The Higgs KK masses remain at the KK-scale $m^2_{h^{(n)},h^{(n)}_\pm,a^{(n)}_0} \approx n^2/R^2 + (m^2_h, m^2_W, m^2_Z)$.
- In the gauge sector, KK mixing occurs due to the EWSB terms in the 5D action.
  B_μ and $W^{3,\pm}_\mu$ KK modes are orthogonal with respect to the modified scalar product.
  Thus, 5D terms $\propto \hat{v}^2 W_\mu W^\mu$, $\propto \hat{v}^2 B_\mu W^\mu$, and $\propto \hat{v}^2 B_\mu B^\mu$ induce KK mixing.
- KK parity is still preserved.

Changing the LKP via boundary localized terms

- Great simplification: The KK mixing terms are bounded by
  $(M^2)_{ij} < g^2 v^2/4$, for $W^{(i)}$-$W^{(j)}$
  $(M^2)_{ij} < g g' v^2/4$, for $W^{3,(i)}$-$B^{(j)}$
  $(M^2)_{ij} < g'^2 v^2/4$, for $B^{(i)}$-$B^{(j)}$
- The diagonal terms receive KK contributions $(M^2)_{ii} > m^2_{w^{(i)},b^{(i)}}$.
- Hence, KK mixing is suppressed. We can treat it as mass insertions.
- $m^2_{W^{\pm,(i)}} \approx m^2_{w^{(i)}} + g^2 v^2/4$.

Changing the LKP via boundary localized terms

The dominant mixing occurs at equal $B^{(i)} - W^{3,(i)}$.
Mass matrix at the first KK level:

$$M^2_{B,W^3} = \begin{pmatrix} m^2_{b^{(1)}} + \frac{g'^2 v^2}{4} & \frac{g' g v^2}{4} \int dy f_{B,1} f_{W,1} \\ \frac{g' g v^2}{4} \int dy f_{B,1} f_{W,1} & m^2_{w^{(1)}} + \frac{g^2 v^2}{4} \end{pmatrix}$$

If BLKTs for B and W are chosen such that
$m^2_{B^{(1)}} + \frac{g'^2 v^2}{4} < m^2_{W^{(1)}} + \frac{g^2 v^2}{4}$, the LKP is W^3-like.

Conclusions

- Respecting all symmetries in UED, for every Standard Model term there exists an a priory free UED parameter corresponding to a boundary localized operator.
- By including BLKTs for the gauge fields, we showed that the UED parameter space contains regions with a W^3-like LKP.
- To our knowledge, models with $W^{3,(1)}$ dark matter have not been discussed in the literature, so far, and in our opinion deserve further studies.
- With LHC on the horizon, and to face the challenges of distinguishing UED from other Standard Model extensions (in particular SUSY), a more complete mapping of the UED parameter space would be desirable.

Outlook

Theory questions:

- Implications of a Higgs BLKT/Is it possible to get $h^{(1)}$ or $a^{(1)}$ LKP?
- Implications for fermion BLKTs?
- One-loop corrections to non-minimal UED?
- How do BLKTs arise from an underlying theory?

Phenomenology of UED with $W^{3,(1)}$ dark matter:

- Changes of UED collider constraints
  - Bounds from non-detection of KK-modes? eg. a la [Rizzo; Macesanu *etal*]
  - Modification of bounds from EWPT ?eg. a la [Appelquist, Yee]
  - Modifications of other collider bounds? see UED review of [Hooper, Profumo]
- Changes to DM bounds:
  - Relic density of the $W^{3,(1)}$ and over closure bound? a la [Servant, Tait; Kong, Matchev]
  - Bounds from direct detection? a la [Servant, Tait II]
  - Indirect detection: ν, $\overline{p}$, e^+, γ, synchrotron radiation, ...?[Hooper, Silk; Hooper, Kribs; Bergstrom *etal*; Brinkmann; ...]

UED as an EFT

The one-loop corrected MUED spectrum:

[Cheng, Matchev, Schmaltz, PRD **66** (2002) 036005, hep-ph/0204342]