KK Parity in Warped Extra Dimension

Work collaborated with K. Agashe, A. Falkowski, and G. Servant: arXiv:0712.2455

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Many ways to slice the space of BSM theories:

- Supersymmetric:

  MSSM, NMSSM, nMSSM, uMSSM, etc.

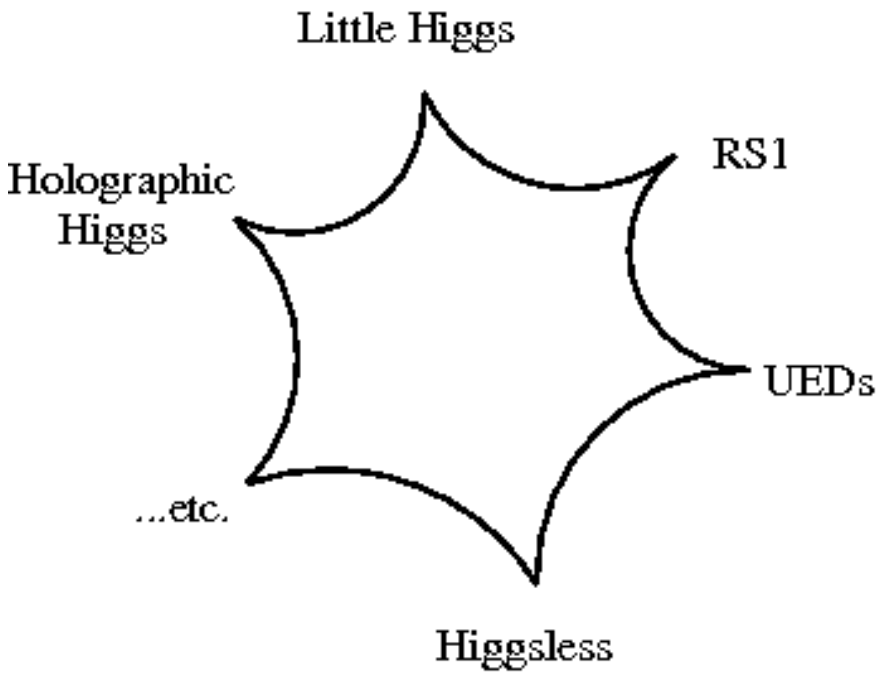
  Essentially they are all cousins of MSSM.

- Non-supersymmetric:

  flat extra-dimension (ADD, UED), warped extra-dimension (RS1), little Higgs, Holographic Higgs, Higgsless, etc.

  It may appear there's a wide range of variety.

- However it now appears that all the seemingly different non-SUSY theories are also related to one another via “AdS/CFT” and/or “deconstruction”.



Some advocated a “little M theory”?
(Cheng, Thaler, Wang ‘06)

Another way to slice the space of BSM theories:

- A new parity @ TeV scale:

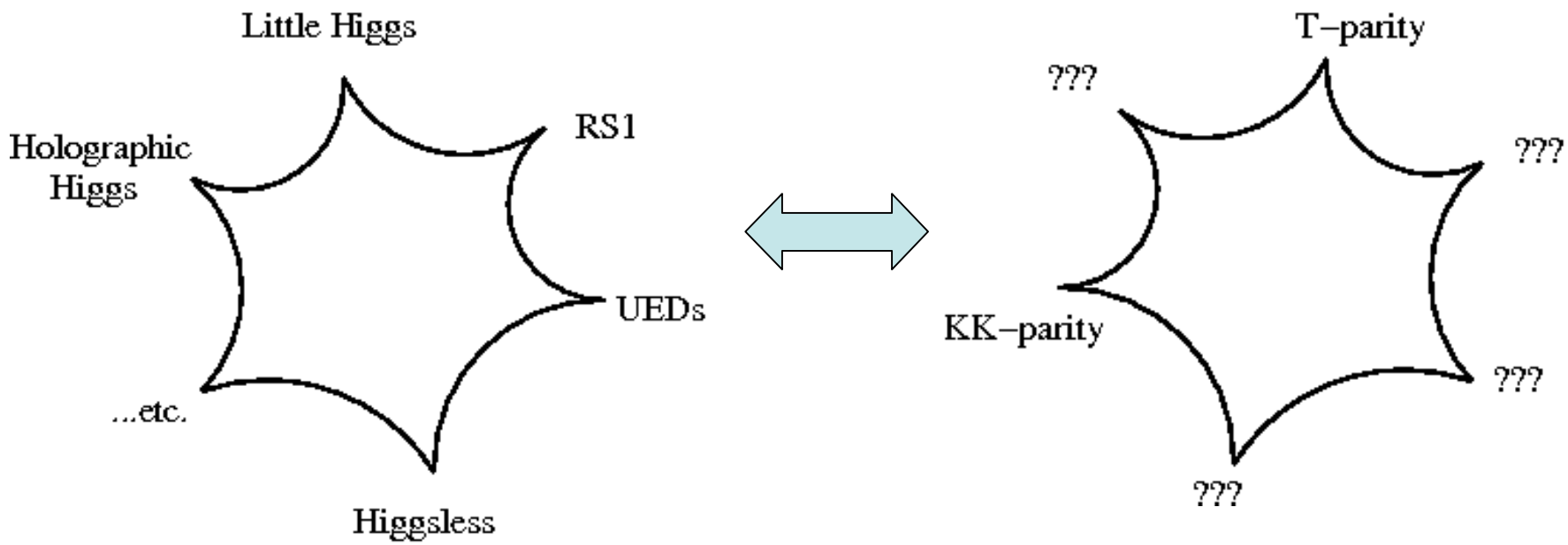
  SUSY (R-parity), flat extra-dimension (KK-parity), little Higgs (T-parity)

- No new parity @ TeV:

  warped extra-dimension (RS1), Holographic Higgs, Higgsless, gauge-Higgs unification.

A Top-Down Viewpoint:

- If we believe there's a continuous spectrum in the space of non-SUSY theories, there ought to be ways to implement the Z_2 parity in models other than little Higgs and UEDs.



A Bottom-Up Viewpoint:

Collider signatures of theories with and without a Z_2 parity are two disconnected sets.

- A new Z_2 parity: Pair-production of parity-odd particles, resulting in missing E_T, multiple jets, and multiple leptons.

  Missing E_T comes from the lightest parity-odd particle if it's neutral. (Also a dark-matter candidate.)

  Events with new particles are always associated with missing E_T.

A Bottom-Up Viewpoint:

Collider signatures of theories with and without a Z_2 parity are two disconnected sets.

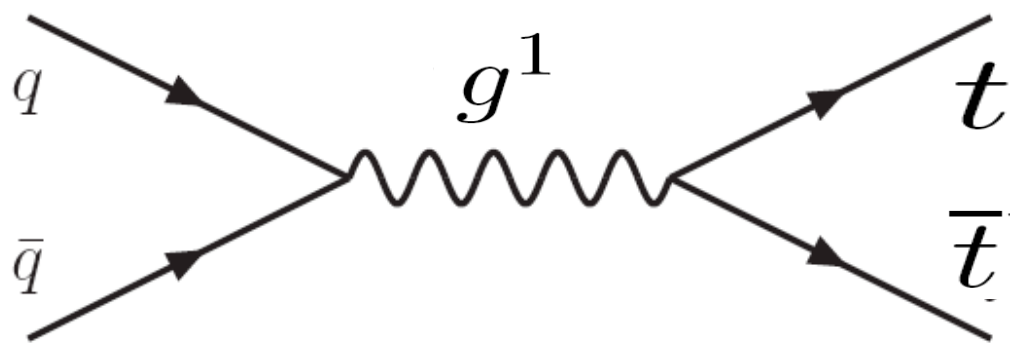
- No new Z_2 parity: new particles can be singly produced. Tend to have a smaller number of jet multiplicity. (Can one quantify the statement?)

  Might not have a dark matter candidate which shows up as missing E_T. Even if there's a dark matter, it does not necessarily show up in every event.

  NOT every event with new particles has associated missing E_T.

At the LHC the KK gluon in RS1 model can be produced through quark - anti-quark annihilation:

$$pp \rightarrow g^1 \rightarrow t\bar{t}$$



The KK gluon can be singly produced. Moreover, if both tops decay hadronically, we would see this as a six-jet event with NO missing E_T.

It is then important to understand whether RS-like models could be implemented with a KK-parity.

If not, and suppose at the LHC we always observe missing E_T in a new physics event, one could immediately disfavor classes of models which cannot accommodate a new Z_2 parity.

The goal of present work is to see if one could implement KK-parity in warped extra-dimensional setup such as RS-like models.

We would like to have an extra-dimensional setup with a warped factor, in which one could have a KK-parity such that

$$\text{KK Parity} = (-1)^n,\ n = \text{KK number}$$

Just like in Universal Extra Dimensions!

(Appelquist, Cheng, and Dobrescu, '00)

However, there's more to the success of UED's than just KK-parity!

if the first KK mode is at 400 GeV, because the geometry is flat the second KK mode will be at 800 GeV, which can be produced singly and couple to the standard model directly.

Why didn't the precision electroweak constraints force the 2nd KK mode to be at 3 TeV, if it has un-suppressed coupling to the SM?

The answer is such couplings are indeed suppressed, albeit *not* due to KK-parity, but due to the (approximate!) KK-number conservation:

$$c\, A_\mu^{(0)} A_\nu^{(0)} \partial_\sigma A_\rho^{(2)}, \quad c = 0!$$

Nevertheless, momentum conservation is broken by interactions living on the two boundaries, which are loop-induced. (Cheng, Matchev, and Schmaltz '02)

If that's the only source of brane-localized interactions, KK-number conservation is still approximate:

$$c \approx \frac{1}{16\pi^2}$$

In warped extra-dimension, there's no (not even approximate!) momentum conservation in the extra-dimension due to the curved background.

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→ The even KK mode needs to be heavier than 2-3 TeV to be consistent with pEW measurements.

(Just like in usual RS models the first KK gauge bosons need to be heavier than 2-3 TeV.)

On the other hand, we still would like an odd KK mode at around 1 TeV or below.

In UED's (as is commonly known), a 1st KK mode at 1 TeV and a 2nd KK mode at 3 TeV is not possible --

KK levels are (roughly) evenly spaced due to flat background. (Unless large brane-localized interactions are introduced.)

However, in warped extra dimensions a small hierarchy between the odd and even KK modes is entirely possible.

The desired low-energy spectrum:

A modest separation between the odd and even modes such that

$$m_{1_-} \sim 1 \text{ TeV}, \quad m_{1_+} \geq 3 \text{ TeV}$$

Let's use the coordinate system:

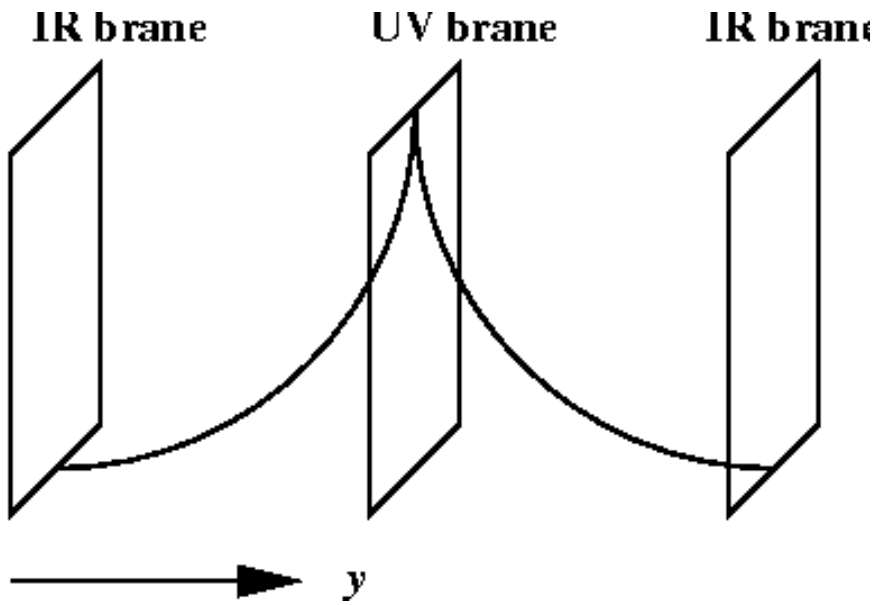
$$ds^2 = a^2(y)(\eta_{\mu\nu}dx^\mu dx^\nu) - dy^2, \quad , -L \leq y \leq L$$

Imposing a Z_2 reflection symmetry in $y \rightarrow -y$ implies

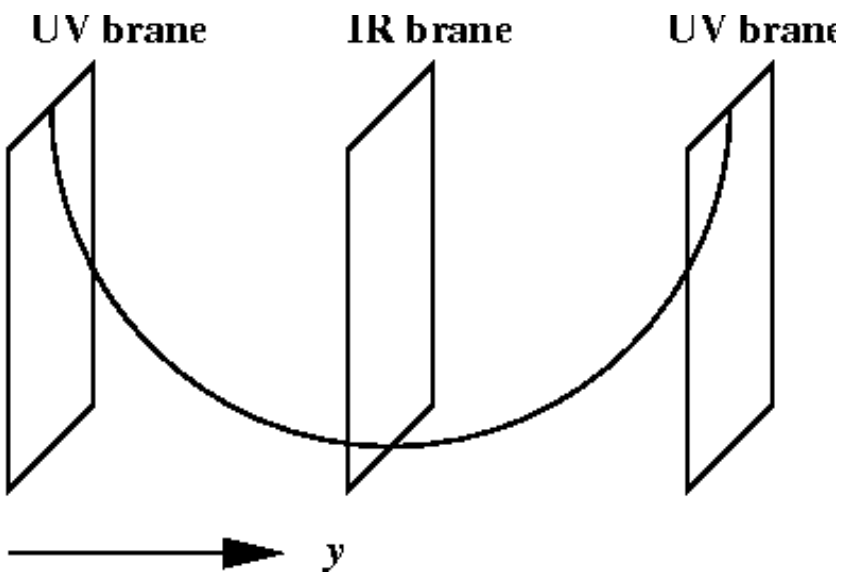
$$a(y) \rightarrow a(|y|)$$

Moreover, we are looking for AdS-like geometry, in that the warped factor is exponential in *y* near the UV region.

Two obvious possibilities: take the original RS1 geometry and reflect with respect to either the UV brane or the IR brane.



$$a(|y|) = e^{-k|y|}$$



$$a(|y|) = e^{k(|y|-L)}$$

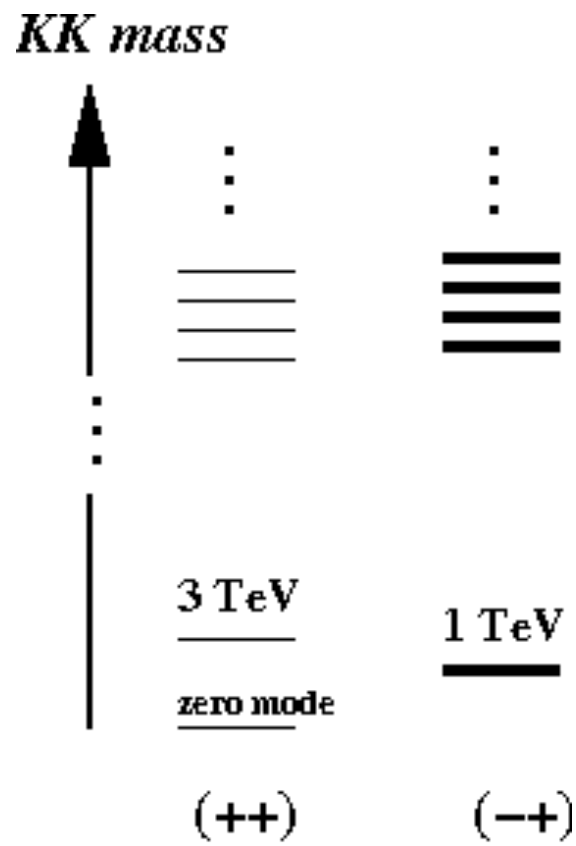
Focus on IR-UV-IR setup

- a modest separation with the even mode at 3 TeV and odd mode 1 TeV is possible only if (very) large brane-localized kinetic term is present:

$$kL \sim 35 \quad \text{and} \quad \frac{m_{1_+}}{m_{1_-}} \approx 3 \quad \rightarrow \quad kr_{IR} \approx 300$$

- Schematically, the KK spectrum looks like

$$m_{KK} = ke^{-kL} \approx 10 - 20\,\text{TeV}$$



- The zero mode profile is constant, and the normalization is dominated by the IR BKT:

$$f_0(y) = \frac{g_5}{\sqrt{2r_{IR}}} = g_0$$

- From this relation one might wonder: if we need VERY large IR BKT to achieve a modest separation between even and odd modes, the bulk gauge coupling g_5 would also need to be large. Then we may suffer a loss of 5D perturbativity….

- Such a large BLK term implies the scale of 5D strong-coupling is close to the KK mass scale:

$$g_0^2 \sim \frac{1}{2}, \ \frac{m_{1_+}}{m_{1_-}} \sim 2, \ kL \sim 30 \quad \rightarrow \quad \Lambda \sim m_{KK} \sim 20 - 30\,\mathrm{TeV}$$

- We may have to give up the Plank/gauge hierarchy if we require a perturbative 5D description at the onset of evenly-spaced KK modes.

  A drawback comparing to the original RS1, but certainly an improvement over UED's. Could at least address the flavor scale at ~ 1000 TeV and above.

As for fermions:

- Constraints from four-fermi operators require the light fermions cannot be too close to the UV. We find that the constraints can be met for $c \sim 0.5 - 0.55$.
- additional mechanism may be necessary to address the flavor problems as well as the Yukawa hierarchy.

The other setup, the UV-IR-UV setup, has a pathological gravity sector and will not be considered here.

Conclusion:

- Implementing KK-parity in warped extra dimension may bring down the mass scale of new particles, allowing them to be (more) accessible at the LHC.

- Two obvious possibilities are gluing two identical copies of AdS_5, either in the UV region (IR-UV-IR) or the IR region (UV-IR-UV).

- The UV-IR-UV setup suffers from instabilities in the gravity sector. IR-UV-IR setup seems more promising in this perspective.

- In the IR-UV-IR setup one may need to lower the scale of the UV brane to lift the 5D strong coupling scale above m_{KK} ~ tens of TeV.

- Flavor issues also cannot be addressed using the usual fashion. Additional mechanisms are necessary.

- Collider signatures of "warped KK-parity" is the hybrid of UED's and RS1:

  1st KK modes need to be pair-produced. The LKP could be a dark matter candidate (either *Z'* or RH neutrino). ➡ UED-like!

  KK masses are <u>*not*</u> evenly spaced. ➡ RS1-like!

- It is also interesting to consider the CFT-dual of our setup. It may serve as the guide to implement T-parity in holographic Higgs and gauge-Higgs unification.

- The CFT-dual may also help realize UV-completion of T-parity in the little Higgs, without resorting to supersymmetrized linear sigma model above 10 TeV.

- Much work remains to be done!