Kaluza-Klein Parity for Randall-Sundrum

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La Thuile, 03.03.2008

Anybody out there?

New physics beyond the standard model probed:

- directly, by LEP and Tevatron, up to $\sim 100 - 250\,\mathrm{GeV}$
- indirectly, by LEP electroweak precision tests, up to $\sim 10\,\mathrm{TeV}$
- indirectly, by kaon mixing up to $\sim 100\,\mathrm{TeV}$
- indirectly, by proton decay even up to $\sim 10^{12}\,\mathrm{GeV}$

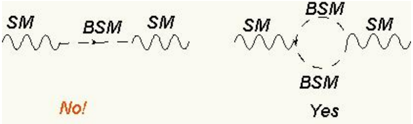
Tension between naturalness and electroweak precision tests

Z_2 vs EW precision tests

The tension can be relaxed if there is a discrete Z_2 parity under which SM is neutral but BSM physics is charged...

- Single vertex with new physics particle is not allowed

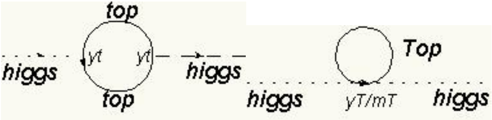
- Corrections to SM gauge boson propagators and four-fermion interaction arises only at one-loop level



We gain the one-loop factor $\sim 1/4\pi^2$ in corrections to EW precision observables, which leaves some room for sub-TeV new physics

Z_2 vs naturalness

Z_2-odd charge of new physics states is compatible with naturalness



$$\Delta m_h^2 \sim -\frac{3}{8\pi^2}\Lambda^2\left(y_t^2 - y_T^2\right)$$

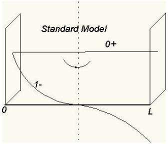
It's all about finding suitable symmetries that would ensure the equality of couplings y_t and y_T...

Examples

Examples of Z_2 parity occurring in "nature":

- R-parity in supersymmetry: all superpartners carry the charge
- T-parity in Little Higgs: lightest BSM gauge bosons carry the charge
- KK parity in Universal Extra Dimensions: first KK level carries the charge

UED



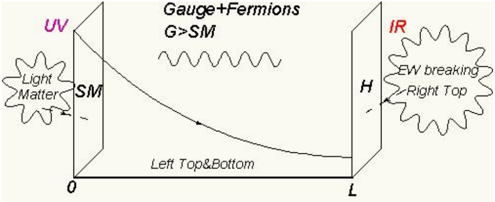
Appelquist,Cheng,Dobrescu [ph/0012100]

- 5D in flat background with all gauge, fermion and higgs fields in bulk
- KK parity as a reflection around the midpoint
- Electroweak precision tests allow for KK modes as light as a few hundred GeV $\rightarrow$ rich LHC phenomenology possible
- The lightest KK odd particle (LKP) could be the KK photon - 1$-$ KK partner of $U(1)_Y$ gauge boson - who is a perfect DM candidate

But neither little hierarchy problem nor flavour problem is addressed

Randall Sundrum

Randall, Sundrum [ph/9905221] + 4000 epigons



- 5D metric warped $ds^2 = a^2(x_5)\eta_{\mu\nu}dx^\mu dx^\nu - dx_5^2$
- Gauge and fermion fields in bulk
- Higgs close to IR brane so as to solve the big hierarchy problem
- Fermion localized in extra dimension $\rightarrow$ theory of flavour from split fermion mechanism
- Higgs as a pseudo-goldstone $\rightarrow$ higgs potential fully calculable, little hierarchy adressed

But RS has no discrete Z_2 symmetry. EW precision tests force KK gauge bosons to be heavier than $3\,\mathrm{TeV}$. Little hierarchy problem strikes back.

Z24RS

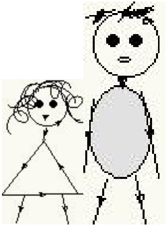
Surprisingly few previous attempts to introduce discrete parity into RS

- Agashe,Servant [ph/0403143] : Z_3 symmetry from 5D warped GUTs. Relevant for DM, not for hierarchy.

Recent developments:

- Agashe,AA,Low,Servant [0712.2455] : KK parity by glueing two copies of AdS space
- Panico,Ponton,Santiago,Serone [0801.1645] : instead of full-fledged KK parity, Z_2 odd partners only for a subset of bulk fields

Randall and Sundrum are, in principle, not interchangable...



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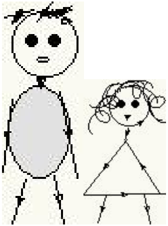
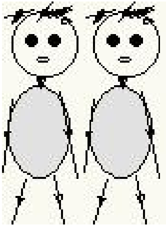


It would be much easier...



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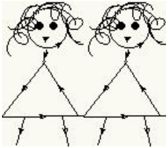
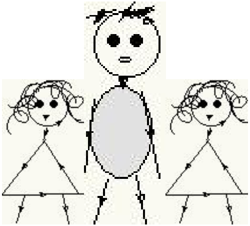
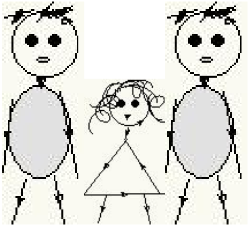


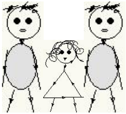
This suggests the solution...

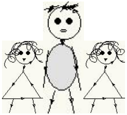


or...



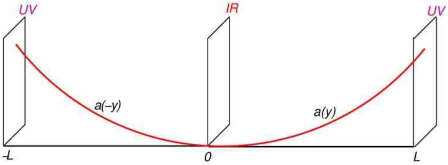
Apparently, there are two alternatives





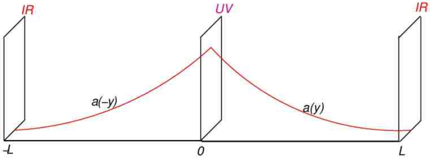
Twofold path

UV - IR - UV model



But, gravitational instability!

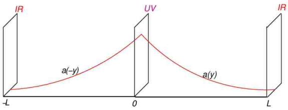
IR - UV - IR model



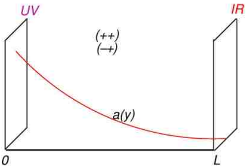
OK, after some massaging

One-slice description

IR - UV - IR model

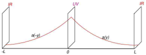


- Even modes are symmetric around midpoint so they satisfy Neumann (+) BC on UV brane
- Odd modes are antisymmetric around midpoint so they satisfy Dirichlet (-) BC on UV brane
- Bulk field with $(+)$ BC in IR brane in two-slice RS correspond to a pair of fields with $(++)$ and $(-+)$ BC in one-slice RS



What we want:

- Lightest KK-even gauge bosons sufficiently heavy, $m_{1_+} > 3\,\mathrm{TeV}$, to avoid problems with EW precision tests
- Lightest KK-odd states fairly light, $m_{1_-} < 1\,\mathrm{TeV}$, to improve naturalness
- Lightest KK-odd particle (LKP) is neutral and weakly interacting, so that it makes a DM candidate



In simplest setups $(++)$ and $(-+)$ towers degenerate, except for zero mode.
In particular $m_{1+} \approx m_{1-}$.
Gauge field **with large BKTs** in warped background

$$\mathcal{L} = -\frac{1}{4} F^{MN} F_{MN} - \frac{1}{4} r_{UV} F^{\mu\nu} F_{\mu\nu} \delta(y) - \frac{1}{4} r_{IR} F^{\mu\nu} F_{\mu\nu} \delta(y - L)$$

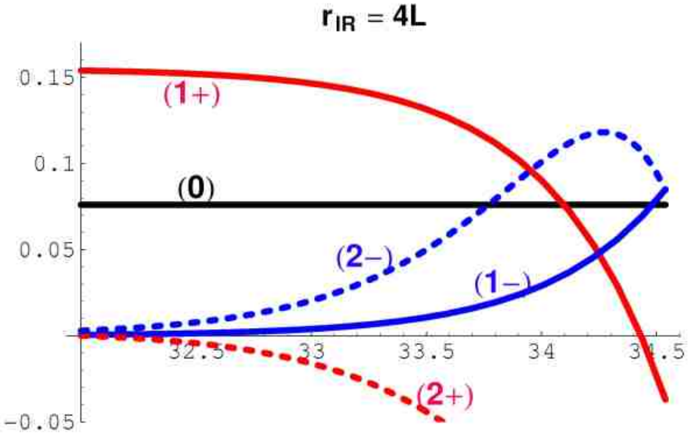
- Zero mode with constant profile in 5D, $m_{0+} = 0$.
- First KK odd mode $m_{1-}^2 \approx \frac{2}{kr_{IR}} M_{\mathrm{KK}}^2$
- First KK even mode $m_{1+}^2 \approx \frac{r_0 + r_{IR} + L}{r_0 + L} \frac{2}{kr_{IR}} M_{\mathrm{KK}}^2$
- Tower of KK even and odd modes starting at $m_n \sim 2.5 M_{\mathrm{KK}}$

Hierarchy between even and odd modes

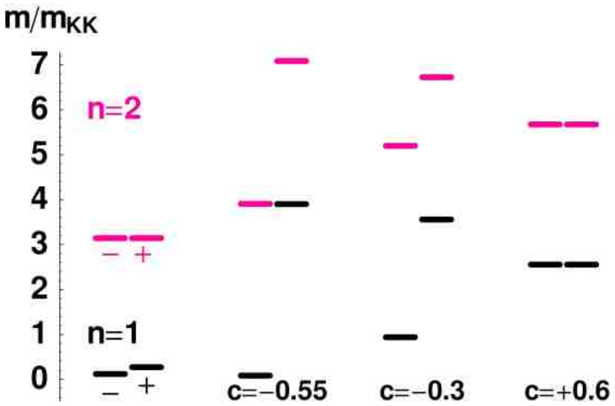
$$\frac{m_{1+}}{m_{1-}} \approx \sqrt{1 + \frac{r_{IR}}{r_0 + L}} \to \sqrt{\frac{r_{IR}}{L}}$$

We need very large IR BKTs, $r_{IR} \gg L$.

Profiles



Spectrum

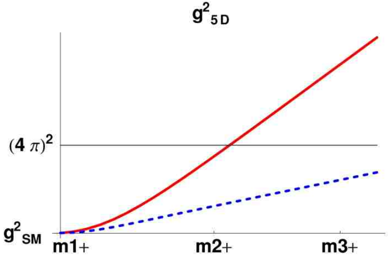


Strong Coupling Problem

Zero mode coupling:

$$g_0^2 = \frac{g_5^2}{L + r_{IR} + r_{UV}} \approx \frac{g_5^2}{r_{IR}}$$

Increasing r_{IR}, we need to increase g_5 to keep the zero mode coupling equal to the SM gauge coupling $g_L^2 \sim 0.5$. This means that the KK modes get more strongly coupled, which may lead to the strong coupling problem.

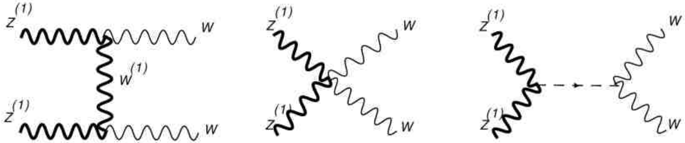


Way out: lower L (Planck-weak hierarchy not explained)

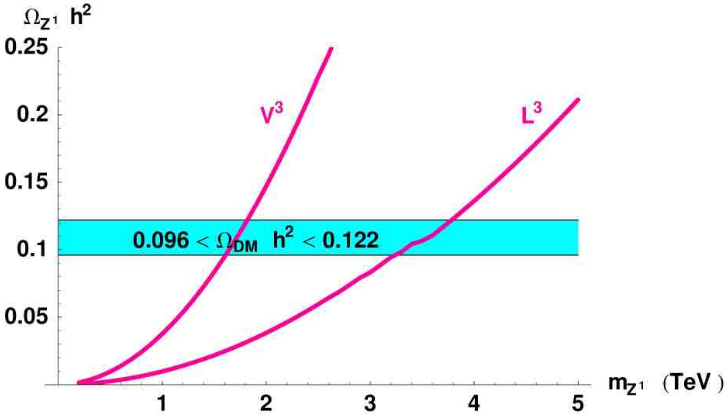
The lightest KK odd partice (LKP) can be

- KK neutrino: KK partner of RH neutrino. But, hard to justify why it should be the lightest
- KK photon: KK partner of hypercharge or $U(1)_X$ gauge boson. But, KK photon has significant coupling only to fermions localized in IR $\longrightarrow$ hard to get large enough annihilation cross-section.
- KK Z: KK partner of neutral $SU(2)_L$ gauge boson. Annihilation cross-section boosted by non-abelian couplings to gauge bosons.
- KK V: In models with custodial symmetry: KK partner the vector combination of $SU(2)_L \times SU(2)_R$ gauge bosons, $V_\mu^3 = (L_\mu^3 + R_\mu^3)/\sqrt{2}$.

Annihilation of KK Z proceeds mainly through non-abelian vertices



KK V similar, but smaller couplings, and no higgs exchange diagram

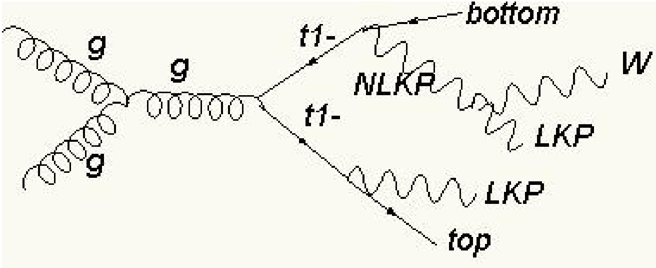

$\Omega_{Z^1}\ h^2$
0.25
0.2
0.15
0.1
0.05
V^3
L^3
$0.096 < \Omega_{DM}\ h^2 < 0.122$
1
2
3
4
5
m_{Z^1} (TeV)

LKP in Colliders

- Tower of KK modes $2\pm$, $3\pm$ starts at $\sim 10\,\mathrm{TeV}$ and is not reachable at the LHC
- First even KK modes $1+$ at $\sim 3\,\mathrm{TeV}$ and difficult to see at the LHC
- By naturalness arguments, we expect at least $1-$ KK modes of SM gauge fields and of the top quark at $\sim 1\,\mathrm{TeV}$.
- KK Z almost degenerate with charged partners (masses split by loop corrections only)

LKP in Colliders

Example:



- Signatures: $t\bar{t}$ + missing energy, $W^+W^-b\bar{b}$ + missing energy, $W^-t\bar{b}$ + missing energy...
- *Difference with RS:* missing energy
- *Difference with UED:* fewer states expected at (sub-) TeV scale, in most economic cases only KK odd partner of gauge bosons and the top quark available at the LHC
- No decent study yet...

Summary

- One can implement KK parity in Randall-Sundrum framework
- Promising scenario: IR-UV-IR model with large brane kinetic terms
- KK Z LKP has relic density in the right ballpark
- Models with pseudo-goldstone higgs and KK parity: *under construction*