The Randall-Sundrum model(s) & its experimental tests

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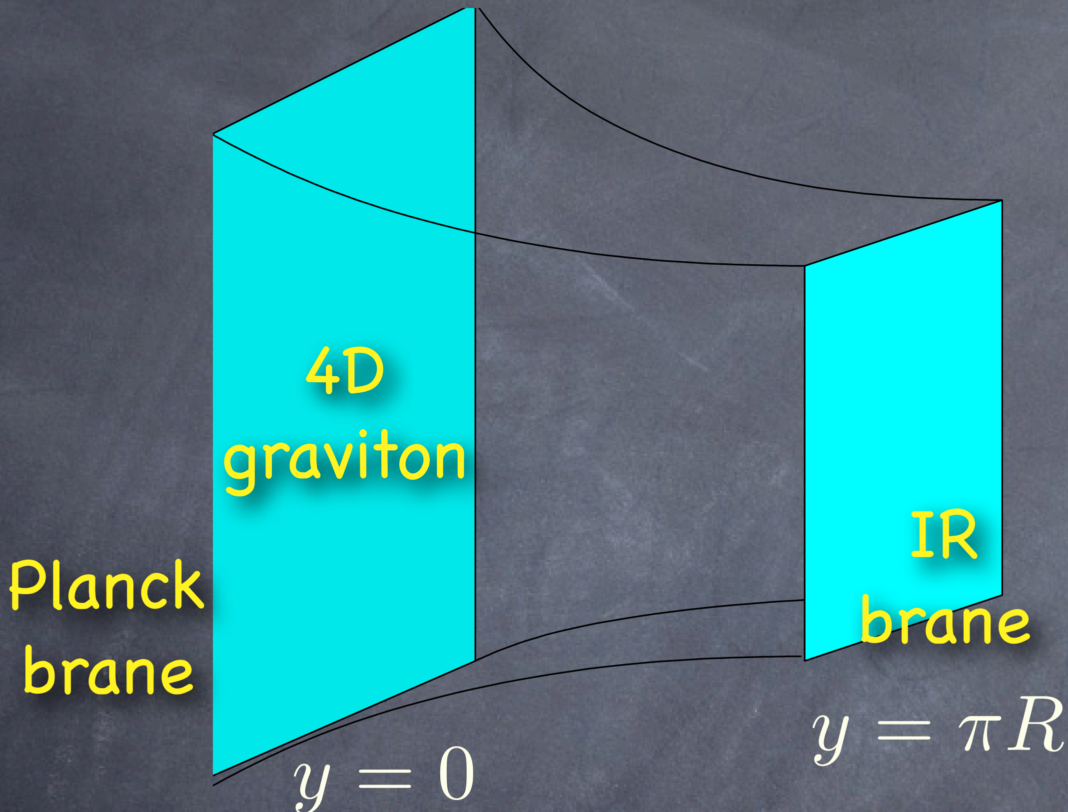
Space-time is a slice of AdS_5



$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

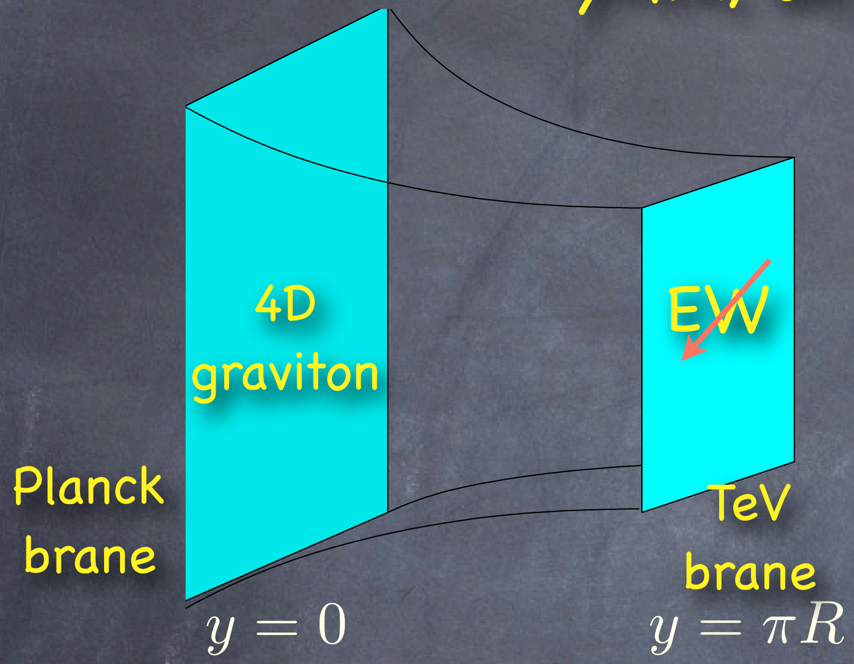
$$M_{Pl}^2 \sim \frac{M_5^3}{k}$$

The effective 4D energy scale varies with position along 5th dimension

RS1 (has two branes) versus RS2 (only Planck brane)

Solution to the Planck/Weak scale hierarchy

The Higgs (or any alternative EW breaking) is localized at y=πR, on the TeV (IR) brane



After canonical normalization of the Higgs:

$$v_{\rm eff} = v_0 e^{-k\pi R}$$

parameter in the 5D lagrangian

$$k\pi R \sim \log(\frac{M_{Pl}}{\rm TeV})$$

Exponential hierarchy from O(10) hierarchy in the 5D theory

One Fondamental scale : $M_5 \sim M_{Pl} \sim k \sim \Lambda_5/k \sim r^{-1}$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

Warped hierarchies are radiatively stable as cutoff scales get warped down near the IR brane

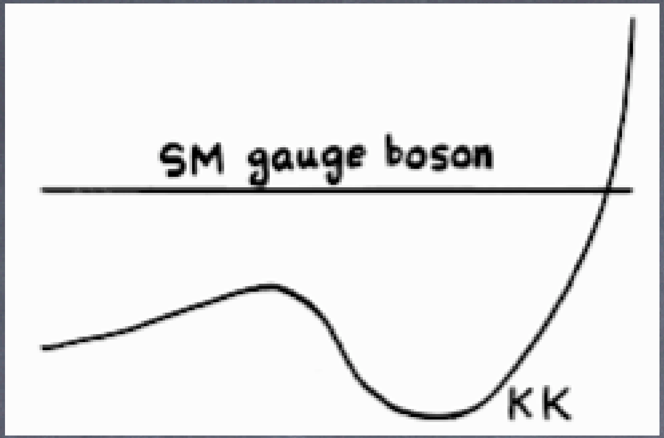
What if the SM (except the Higgs) live in the bulk?

Need to solve the wave equations in curved 5D spacetime

=> Profiles of KK modes are peaked near the TeV brane

What about the profiles of the zero (SM) modes?

Gauge bosons



couplings of particles
=
overlap of profiles in extra dim

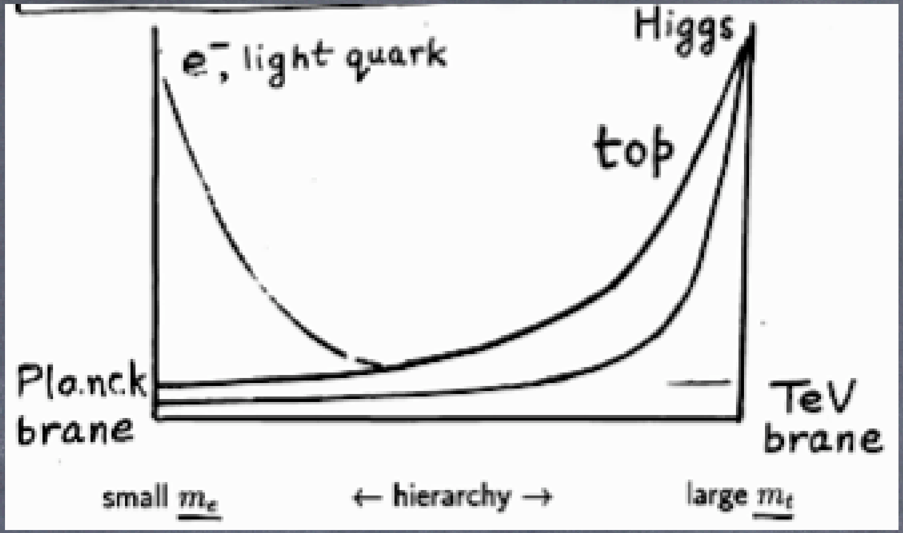
Couplings of gauge zero modes to any fermions (SM or KK) are universal, as guaranteed by 4D gauge invariance

Couplings of KK gauge bosons to matter localized on IR brane: too large

-> Need to delocalize fermions in the bulk as well profiles= solutions to the wave equation in curved 5D spacetime

Fermions

Lightest mode (SM) is sensitive to the 5D bulk mass



[Grossman, Neubert '99]
[Gherghetta, Pomarol '00]

Solution to the Flavor puzzle

First two generations near Planck brane:
FCNCs from higher dimensional operators are suppressed.

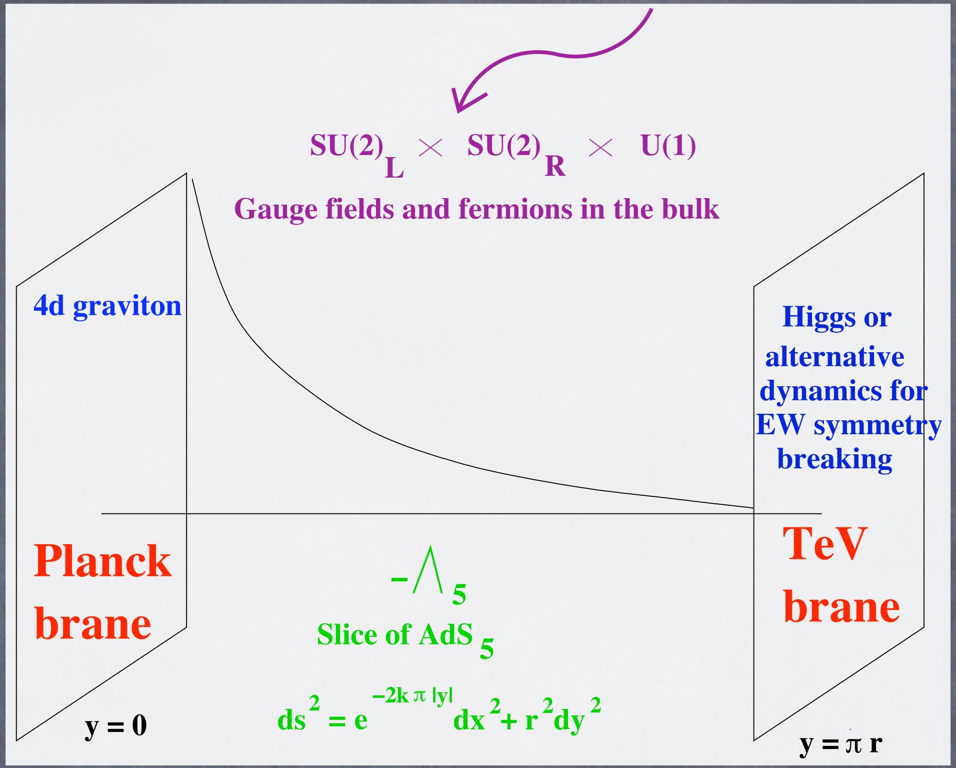
No hierarchy in 5D theory.

Particle physics model building in warped space

2006 favourite set-up:

✔ hierarchy pb
✔ fermion masses
✔ High scale unification
✔ FRW cosmology

✔ Still active research on consistency with EW precision tests & little hierarchy pb



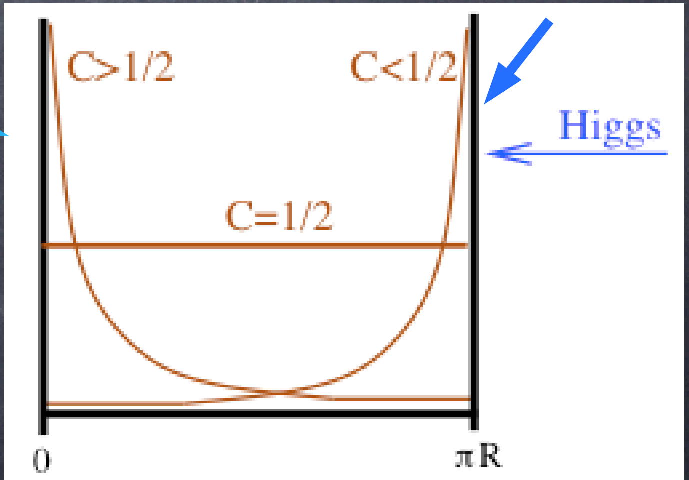
Note: No susy here

and many different realizations

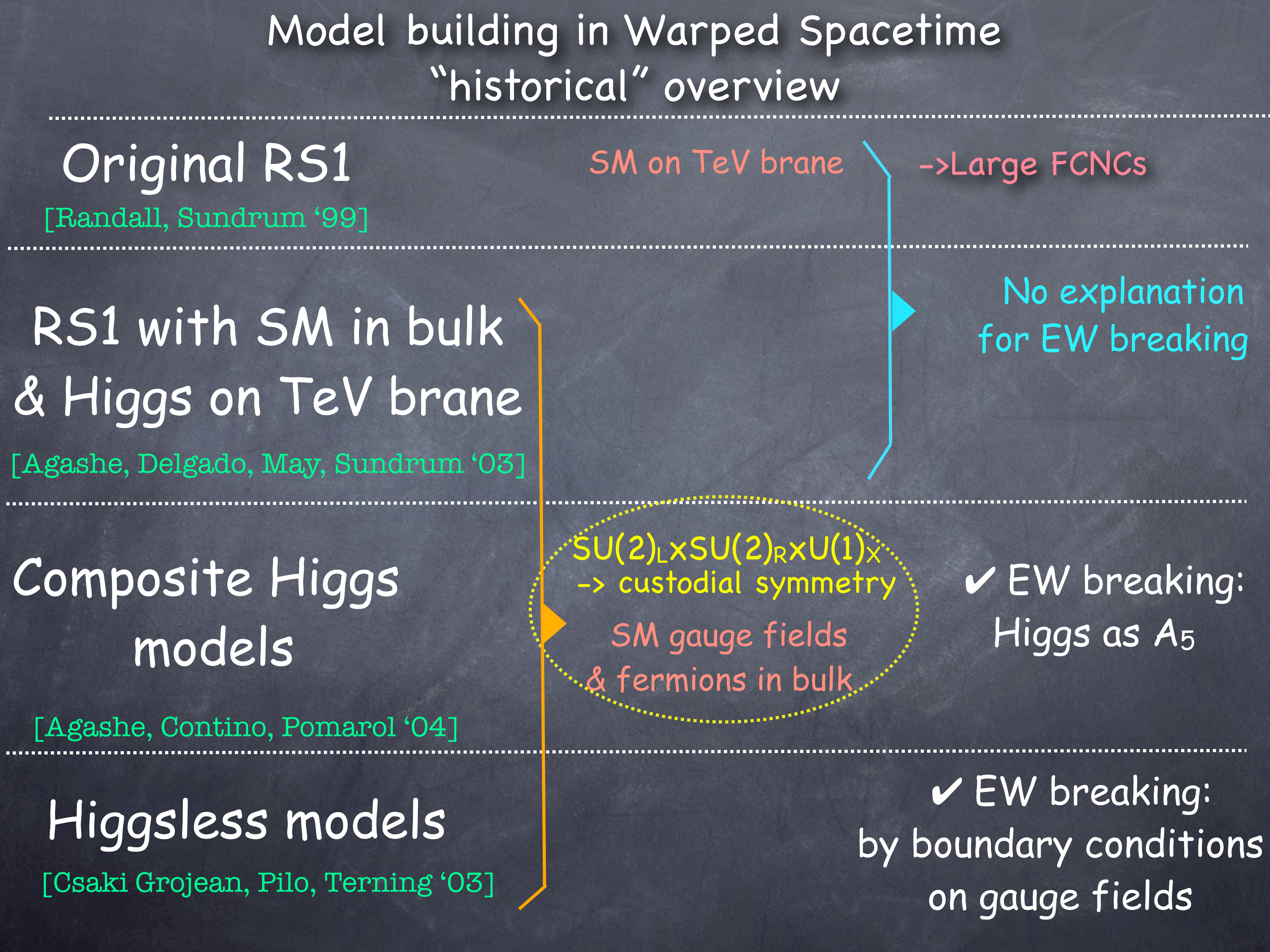
M_{KK}~few TeV

light fermions

heavy fermions



[Grossman, Neubert '99]
[Gherghetta, Pomarol '00]



Model building in Warped Spacetime
"historical" overview
Original RS1
[Randall, Sundrum '99]
SM on TeV brane
->Large FCNCs
RS1 with SM in bulk
& Higgs on TeV brane
[Agashe, Delgado, May, Sundrum '03]
No explanation
for EW breaking
$SU(2)_L \times SU(2)_R \times U(1)_X$
-> custodial symmetry
SM gauge fields
& fermions in bulk
Composite Higgs
models
[Agashe, Contino, Pomarol '04]
✔ EW breaking:
Higgs as A_5
Higgsless models
[Csaki Grojean, Pilo, Terning '03]
✔ EW breaking:
by boundary conditions
on gauge fields

AdS/CFT dictionnary

[Maldacena '97]
[Arkani-Hamed, Porrati, Randall '01]
[Rattazzi, Zaffaroni '01]

RSI ⟷ An almost CFT that very slowly runs but suddenly becomes strongly interacting at the TeV scale, spontaneously breaks the conformal invariance and confines, thus producing the Higgs

The hierarchy problem is solved due to the compositeness of the Higgs

KK modes localized on TeV brane ⟷ bound state resonances

A gauge symmetry in the bulk ⟷ A global symmetry of the CFT

$SU(2)_R$ will protect the rho parameter

[Agashe, Delgado, May, Sundrum '03]
[Csaki, Grojean, Pilo, Terning '03]

UV matter ⟷ Fundamental particles coupled to the CFT

IR matter ⟷ Composite particles of the CFT

RSI: A calculable model of technicolor

Signatures

some examples

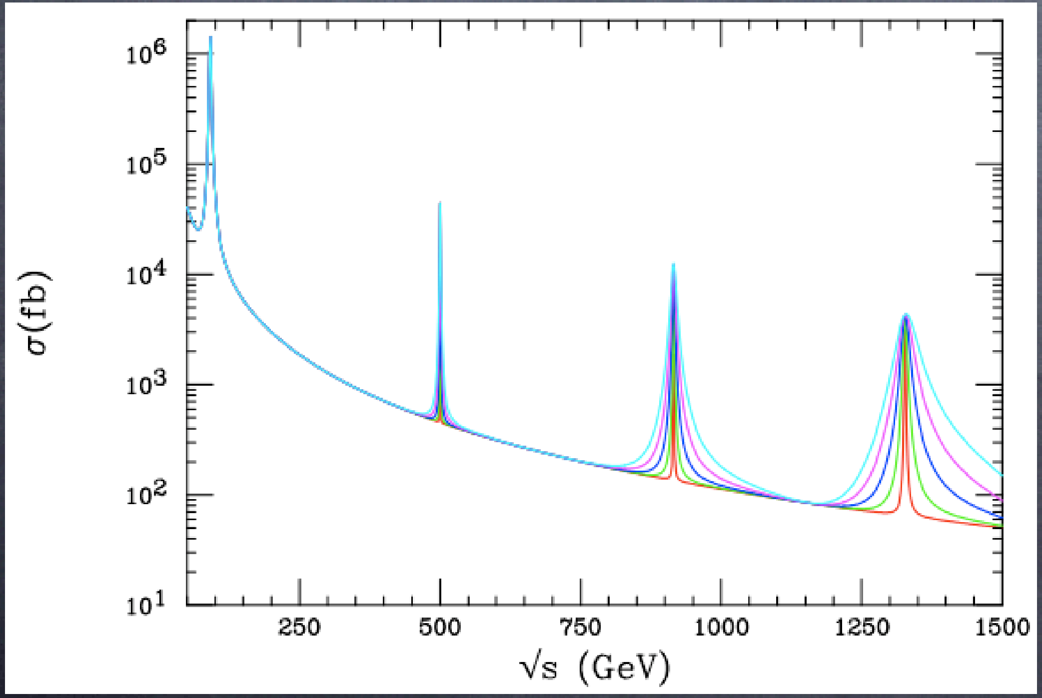
KK gravitons

✗ Discrete spectrum with KK states non regularly spaced (proportional to the zeros of Bessel functions)

✗ $\Delta m \sim O(\text{TeV})$

✗ Each KK graviton couples as 1/TeV and not $1/M_{Pl}$

$$e^+e^- \to G^{(n)} \to \mu^+\mu^-$$



only in original RS1 !
(if fermions
on TeV brane)

Signatures involving KK gauge bosons

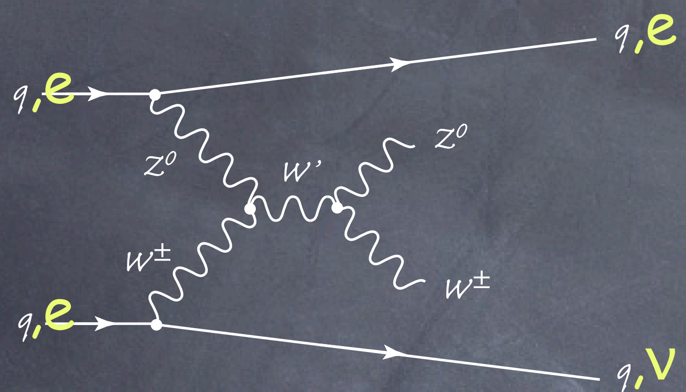
- Deviations in the gauge bosons self-couplings
  - in models with a Higgs: Higgs couplings to EW gauge KK modes are enhanced by $\sqrt{(k\pi R)}$ so longitudinal W,Z fusion into EW KK modes is enhanced
  - in higgsless theories, typically 1%-5% deviations compare to the SM self-couplings

Precise measurements at the ILC appear to be necessary for the ultimate test of Higgsless models

In particular:
Tests of the mechanism of partial unitarity restoration in the longitudinal vector boson scattering

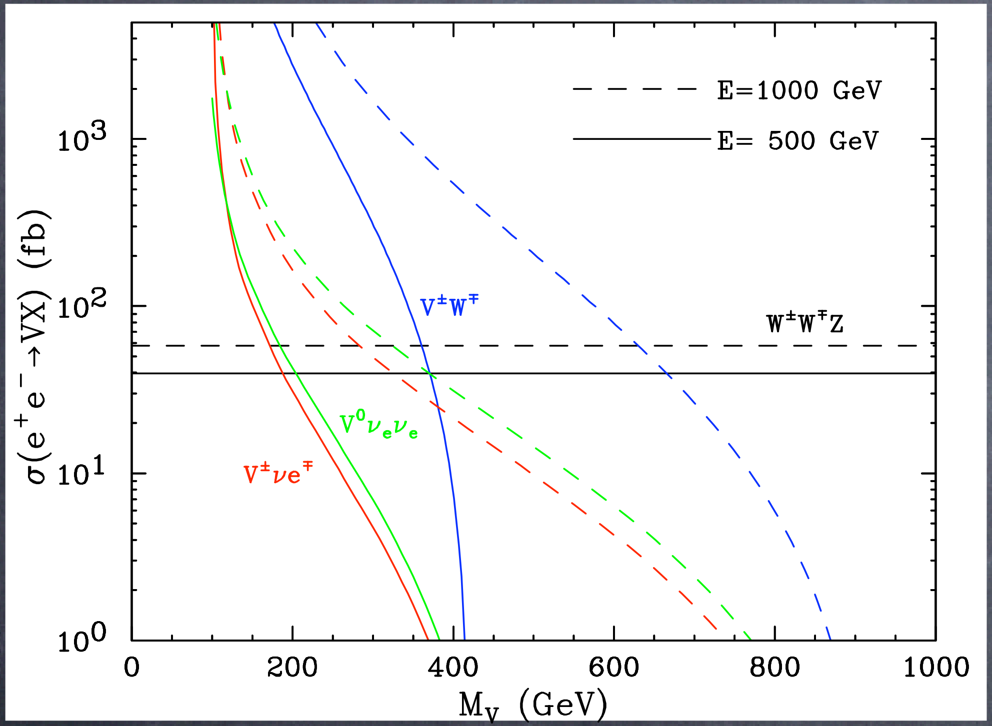
[Birkedal, Matchev, Perelstein '05]

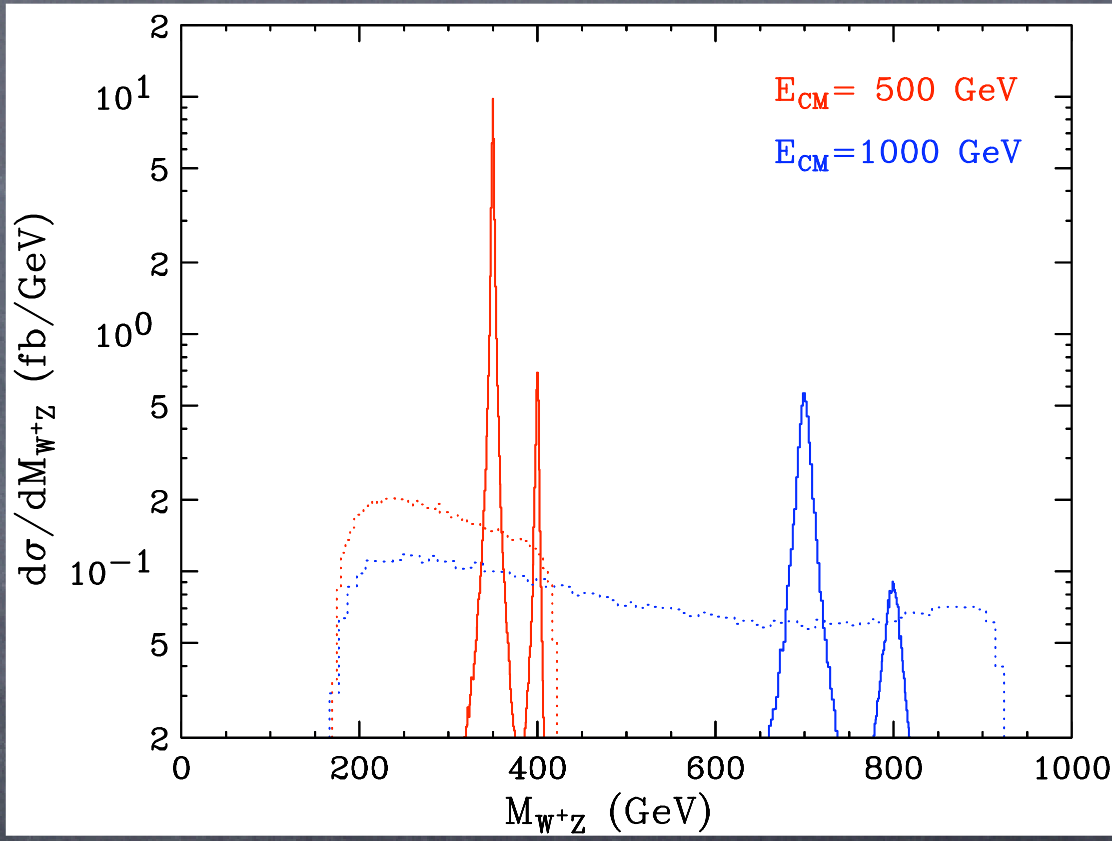
WZ elastic cross section



$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \qquad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

a narrow and light resonance





Left: V_1 production cross-sections and the continuum SM background at an e^+e^- lepton collider of center of mass energy 500 GeV (solid) or 1 TeV (dashed). Right: WZ invariant mass distribution for Higgsless signals (solid) and SM background (dotted), at $E_{CM} = 500$ GeV (red, $M^\pm = 350, 400$ GeV) and $E_{CM} = 1$ TeV (blue, $M^\pm = 700, 800$ GeV).

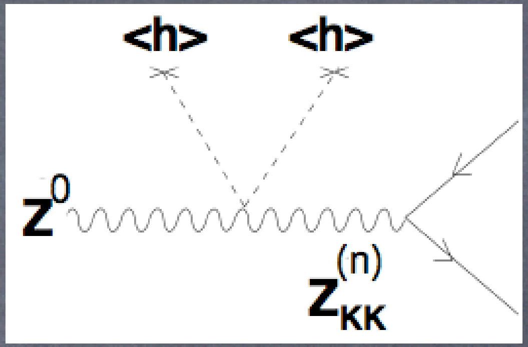
Signatures involving fermions

- Non-universality of the couplings gauge boson/fermions

dual picture: fermion masses are generated from the interaction to the strongly coupled sector

fermion mass ⇔ wavefunction profile in the bulk

different masses ⇔ different couplings to W and Z



First two generations

$$\frac{\delta g_{SM}}{g_{SM}} \approx \mathcal{O}\left(\frac{m}{\mathrm{TeV}}\right) \approx 0.1\% \text{ at most}$$

Third generation

$Z_{b_L \bar{b}_L}$ deviations

severe constraints

How to get large top mass without spoiling the Zbb coupling?

New source of FCNCs involving light fermions
are suppressed due to small overlap
between light fermions and gauge KK modes.

However sizable FCNCs involving the top

$$e^+e^- \to Z \to t\bar{c}$$

[Agashe, Perez, Soni '06]

More on Zbb

As noticed recently, custodial symmetry might be helpful to protect $Z_{b_L \bar{b}_L}$

[Agashe, Contino, Da Rold, Pomarol '06]

usual $SU(2)_L \times SU(2)_R \times U(1)_X$ embedding

$$Q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix} \equiv (2,1)_{1/6} \qquad Q_R = \begin{pmatrix} t_R \\ b_R \end{pmatrix} \equiv (1,\bar{2})_{-1/6}$$

RH fermions are promoted to $SU(2)_R$ multiplets, the new components have no zero mode

other embedding

$$Q_L = \begin{pmatrix} t_L^{2/3} & t_L^{5/3} \\ b_L^{-1/3} & b_L^{2/3} \end{pmatrix} \equiv (2,\bar{2})_{2/3}$$

then b_L is an eigenstate of L ⇔ R and this ensures that $\delta Z_{b_L \bar{b}_L} = 0$

but we expect deviations in

$Zt_L\bar{t}_L$ $\quad Wt_L\bar{b}_L$ $\quad Zb_R\bar{b}_R$

will be measured at LHC/ILC

(good for A^b_{FB})

[Djouadi, Moreau, Richard '06]

Production of KK fermions at colliders

KK modes in realistic RS models are accessible at colliders in contrast with previous thoughts

Mass spectrum of KK fermions

Depends on:

✔ type of boundary conditions on TeV and Planck branes

✔ c-parameter (=5D bulk mass)

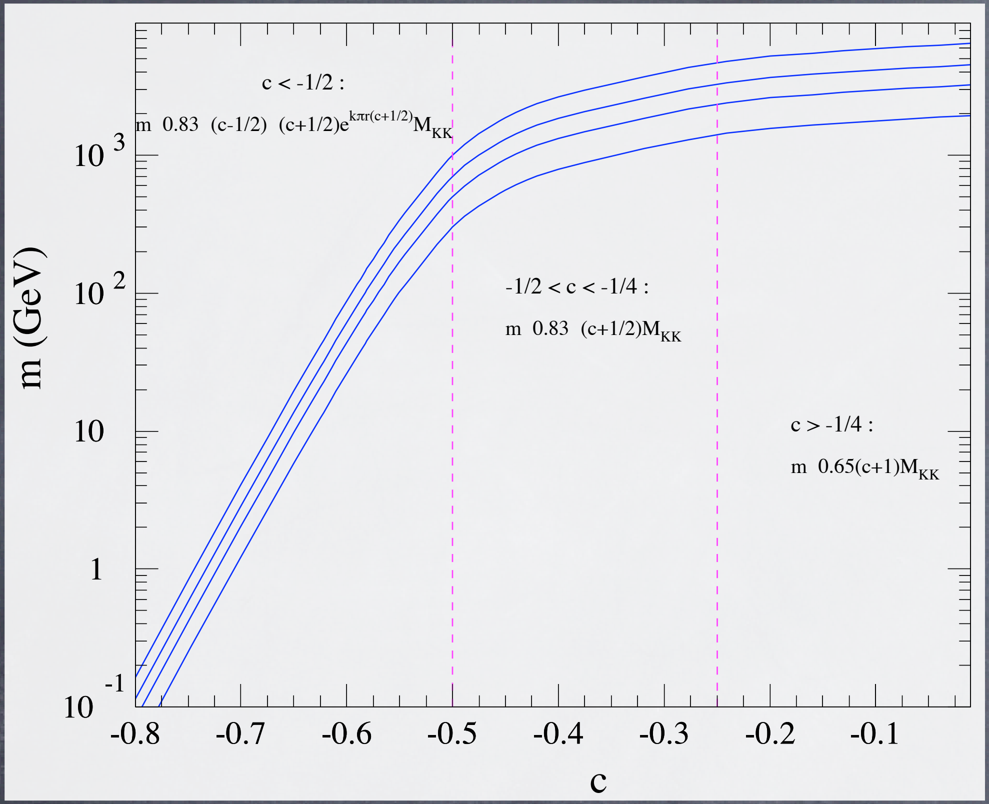
(=localization of zero-mode wave function)

Fermions with Dirichlet BC on Planck brane and Neumann BC on TeV brane do not have zero modes (-+). Their first KK mode can be lighter than the mass of KK gauge bosons

e.g. the KK partners in the $SU(2)_R$ multiplet of t_R

$\Rrightarrow$ Not a single KK scale

Mass spectrum of lightest KK fermion



10 TeV
7 TeV ← M_{KK} value
5 TeV
3 TeV

c= 5D fermion mass
in Planck units

Agashe-Servant
hep-ph/0403143,
hep-ph/0411254

Right-handed top quark has c ≈ -1/2 ⇛ (-+) KK modes in its multiplet have mass of a few hundreds of GeV: Accessible at LHC!

Light KK fermions are expected as a consequence of the heaviness of the top quark

We focus on the KK RH bottom quark belonging to the t_R multiplet, denoted $\tilde{b}_R$

This mode mixes with the SM bottom quark and in minimal models, it induces large corrections to the $Zb\bar{b}$ coupling

This leads to a strong constraint on $\tilde{b}_R$ mass: ≥ 1.5 TeV

However, Agashe-Contino-Da Rold-Pomarol (hep-ph/0605341) have recently proposed a solution to protect the $Zb\bar{b}$ coupling

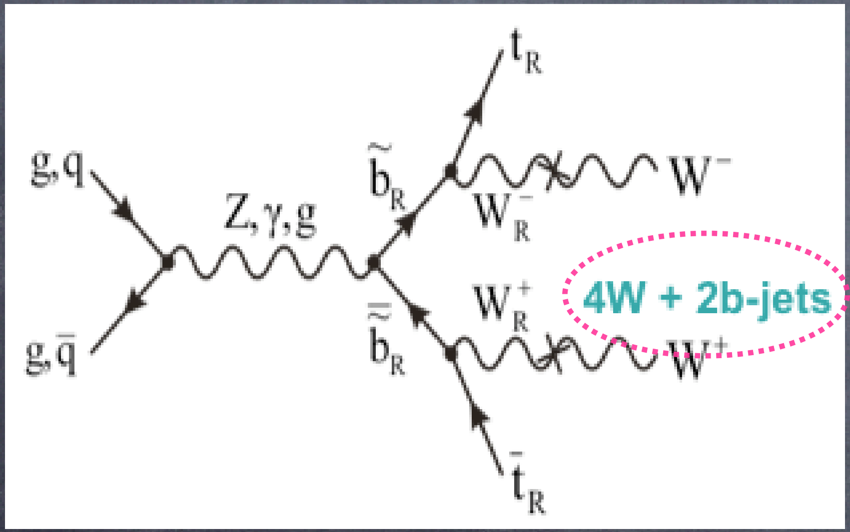
$\tilde{b}_R$ is likely to be the lightest KK state in these new models and could be produced at LHC & ILC

Approximately half of its decays are into tW so that one main signature associated with its pair production is 4W+2b

Multi W final states

[Dennis, Karagoz-Unel, Servant,Tseng, in preparation]

These can arise from the production and decay of Kaluza-Klein fermions in Randall-Sundrum models with $SU(2)_L \times SU(2)_R$ EW gauge group in the bulk.

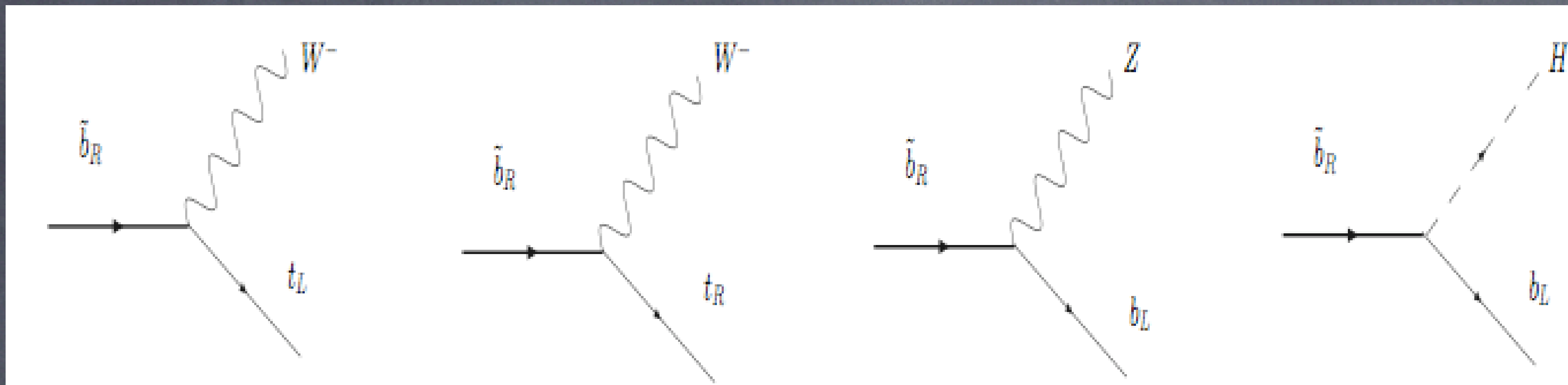


At LHC, the main backgrounds are from $t\bar{t}$ and $t\bar{t}H$

$t\bar{t}$ -> 2W+2b and 4 misidentified extra jets : no such background at ILC

$t\bar{t}H$ -> exactly 4W+2b
but significant background only for large $\tilde{b}_R$ mass

The four decay channels of $\tilde{b}_R$



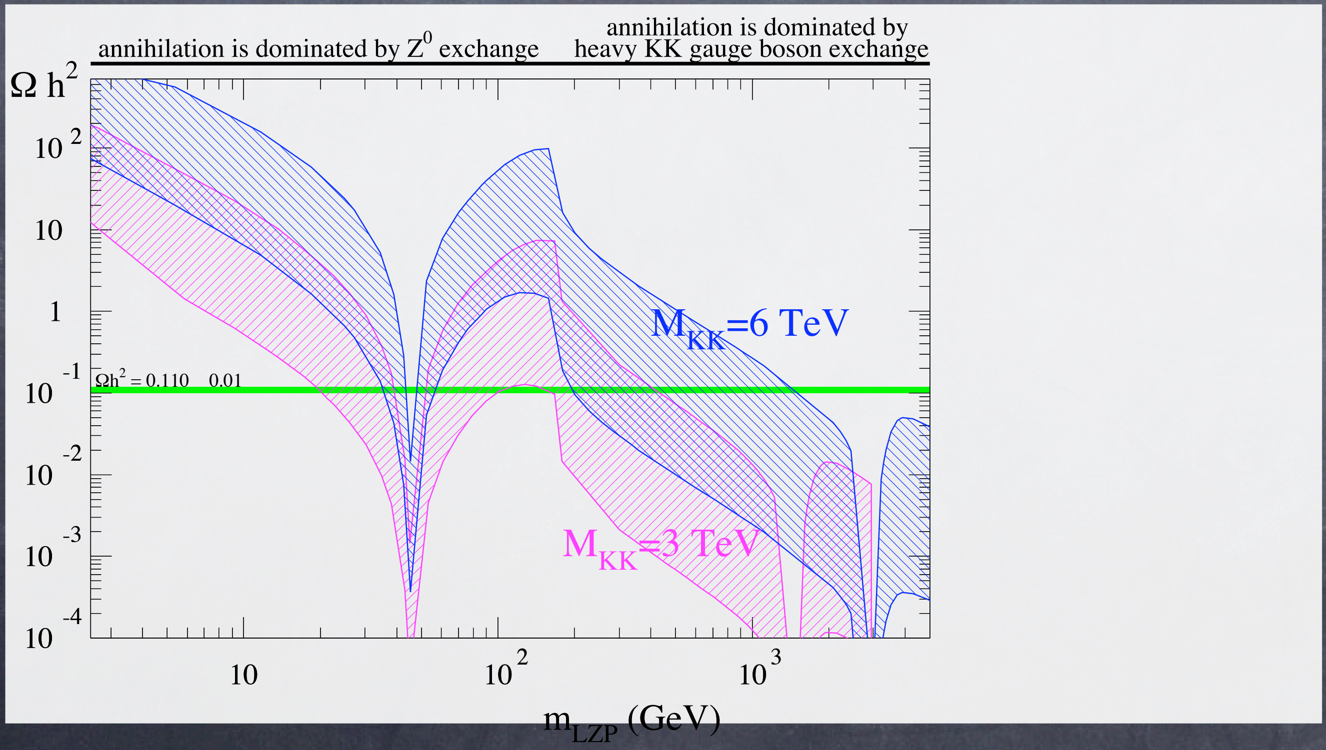
comes from W_R-W mixing

come from Yukawa coupling between (t_L,b_L) and (t_R, $\tilde{b}_R$)

Cosmology

The Lightest Kaluza-Klein particle as dark matter

e.g. KK RH neutrino dark matter



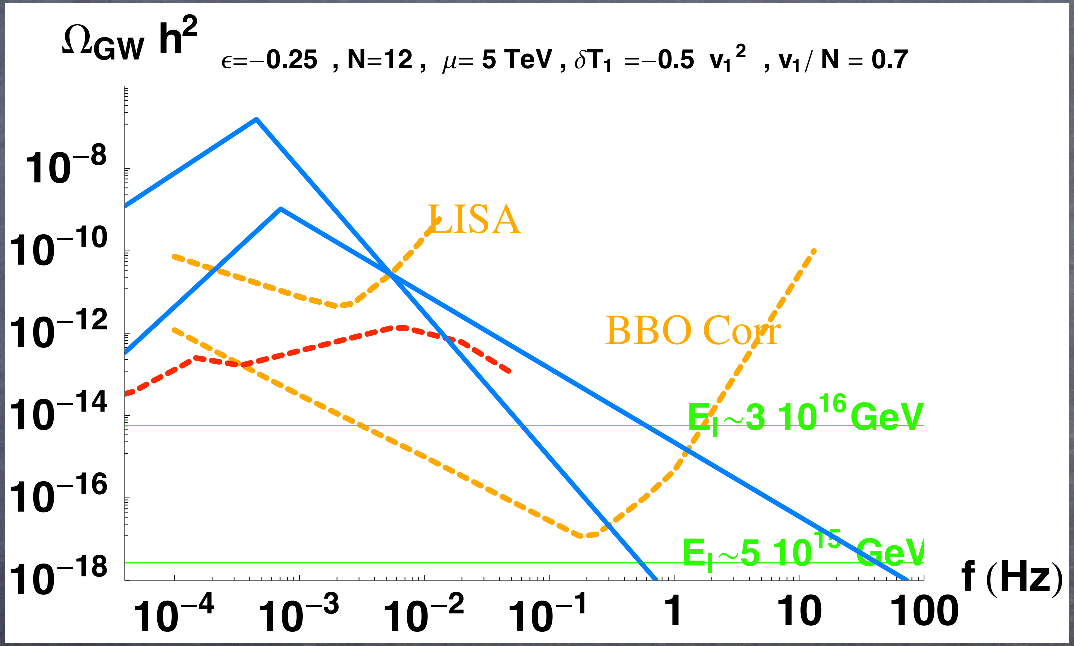
[Agashe, Servant ‘04]

Searching for Warped Geometry with Gravity Waves

[Randall, Servant '06]

Gravitational Waves from "3-brane" nucleation:

Signal versus LISA's sensitivity



Signature in GW is model-independent, in contrast with Kaluza-Klein collider signatures which depend on the details of the model

but crucially depends on the radion properties

Summary

RS1 = A compelling alternative to SUSY

In its best formulation, it addresses:

hierarchy pb
EW breaking
dark matter
unification

+ An explanation for the flavor hierarchy

A rich phenomenology, a large variety of signatures

An interesting dual description of strongly coupled 4D theories

= calculable technicolor models