Randall-Sundrum Model-Building

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New physics is required to address the open questions left by the Standard Model.

"New physics" requires new particles that can in principle be discovered.

For issues connected to the Higgs boson, these particles are needed to cancel the quadratic divergences of the Higgs mass term

and, more generally, to provide a means to calculate a finite and definite prediction for the Higgs potential.

But, these particles have not been discovered at the LHC.

How far away can they be ?

In models of SUSY, this is already a serious problem:

all parameter sets proposed before 2010 are now excluded (including those for “split SUSY”).

The current limit $m(\widetilde{g}) > 1.8 \ \mathrm{TeV}$ is troubling for models of “natural SUSY”. (Maybe this means that must soon appear.)

A different approach to explain the Higgs boson properties is “composite Higgs”.   Here, at least, the predictions are not so tight, and it is unclear how much of the full parameter space is excluded by the LHC experiments.

However,

precision electroweak provides strong constraints

no 2-body bosonic resonances are seen at LHC up to about 2 TeV

the correction to the Higgs boson mass from the top quark

$$\delta\mu^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

seems to require top quark partners close to 1 TeV.

But, the most important problem with composite Higgs models is that there is no predictive model.

Composite Higgs models have many signatures. Often these are described by effective high-dimension operators. A model is needed to compute the operator coefficients and to relate these coefficients and their observable effects.

So, how can we build explicit models of composite Higgs that address all consequences of this idea ?

How can these models contain a little hierarchy needed to avoid constraints from particle searches at the LHC ?

These questions can be addressed by 3 ideas:

Randall-Sundrum construction

Higgs as a Goldstone boson

Phase transition in fermion condensation

These ideas were actively pursued in the early 2000's by

Arkani-Hamed, Cohen, Katz, Nelson
Agashe, Contino, Pomarol
Hosotani;   Nomura

and many others.   It is time to go back and try to make more progress.

Randall-Sundrum construction

Replace strong-coupling dynamics of a 4-d theory with weak-coupling dynamics of a 5-d theory in anti-de Sitter space

as motivated by the AdS/CFT correspondence of string theory.

4d	5d
bound states	Kaluza-Klein excitations
global symmetries	gauge symmetries
Higgs scalar fields	A_5^A (gauge-Higgs unification)

Higgs as a Goldstone boson

Symmetry breaking at a high scale Λ leads to a multiplet of Goldstone bosons. These can contains the full SU(2)xU(1) Higgs doublet φ. The Higgs potential is flat to first approximation, shaped by (calculable?) global-symemtry-breaking perturbations.

Some problems with precision electroweak formerly associated with the TeV scale can now be moved to Λ.

Phase transition in fermion condensation

Models with Goldstone bosons and dynamical symmetry breaking have potentials depending on a nonlinear sigma model field U with

$$U = \exp[2i\pi^a t^a / F]$$

Such potentials are typically minimized at

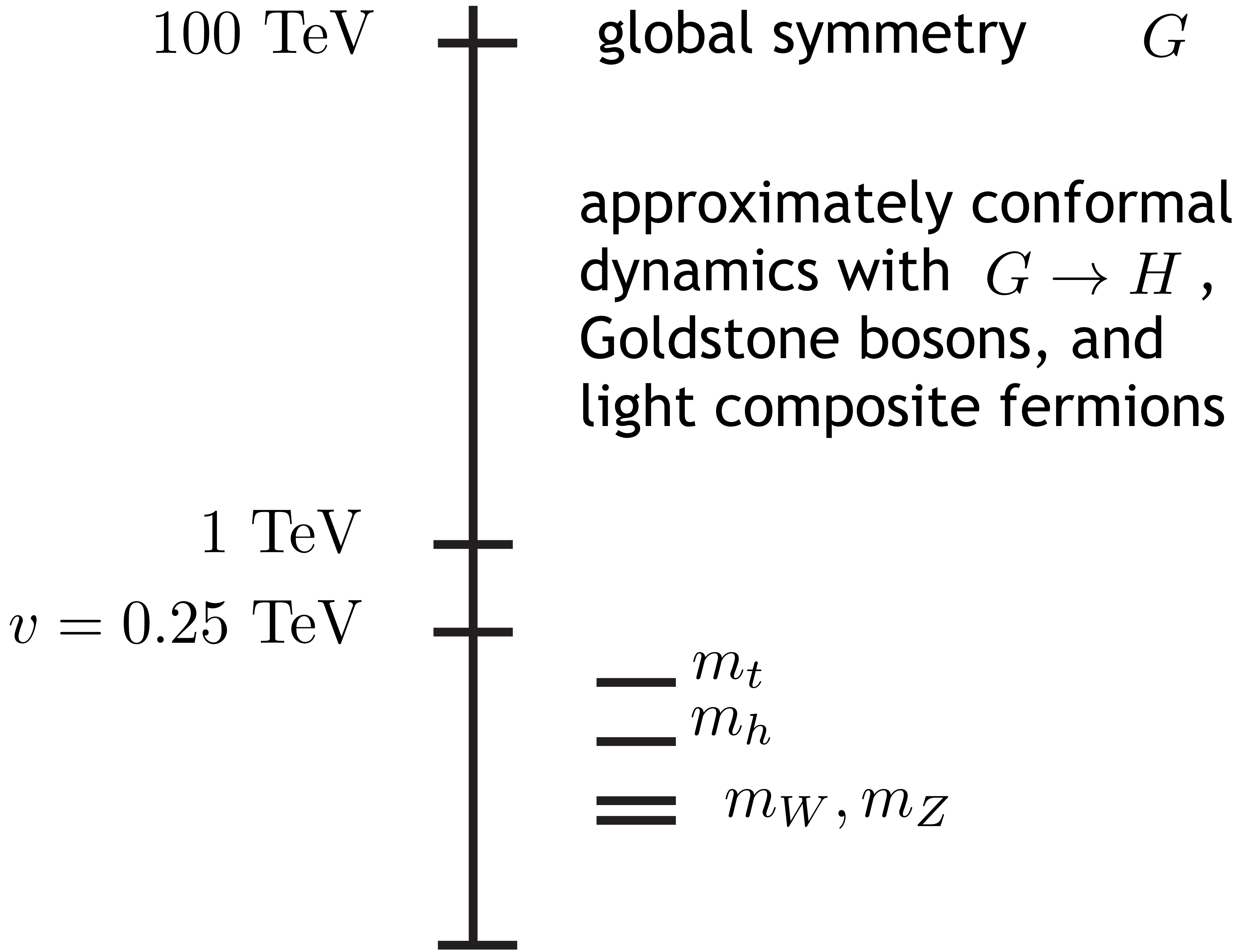
$$\langle 1 - U \rangle = \mathcal{O}(1) \qquad v/F \sim 1$$

This limits the smallness of v/m_{KK} .

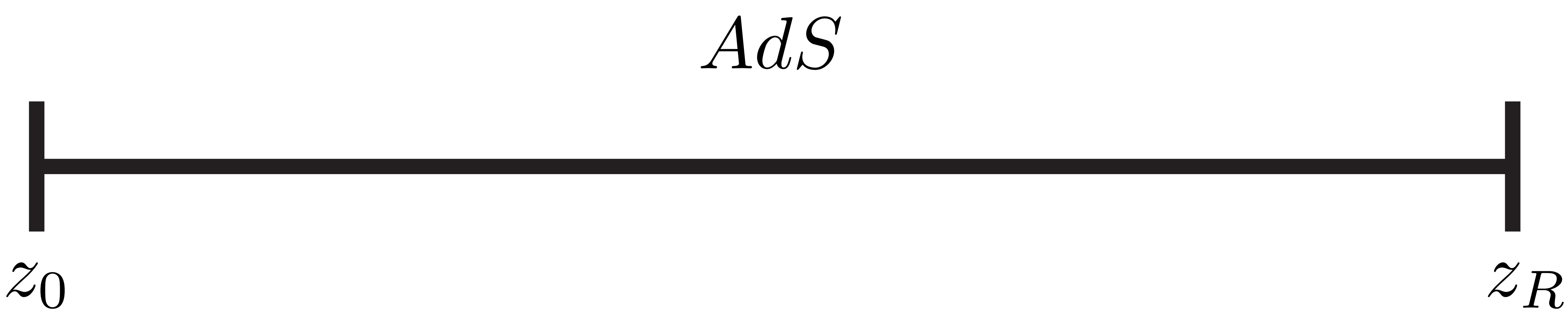
If the 5-d theory has a nontrivial phase diagram, we can find 2nd order phase transitions where $v/F \to 0$.

Fine tuning to such points in 5-d might not be fine-tuning in 4-d.

Physical picture:



Physical picture in 5-d



$(kz_0)^{-1} \sim 100 \text{ TeV}$ $\qquad\qquad$ $(kz_R)^{-1} \sim 1 \text{ TeV}$

The upper limit on z_R is set by the S parameter

$$(kz_R)^{-1} \sim 1 \text{ TeV} \quad \rightarrow \quad m_{KK} \sim 3 \text{ TeV}$$

Realization of gauge symmetries:

bosons of G : A_m^A A_5^A

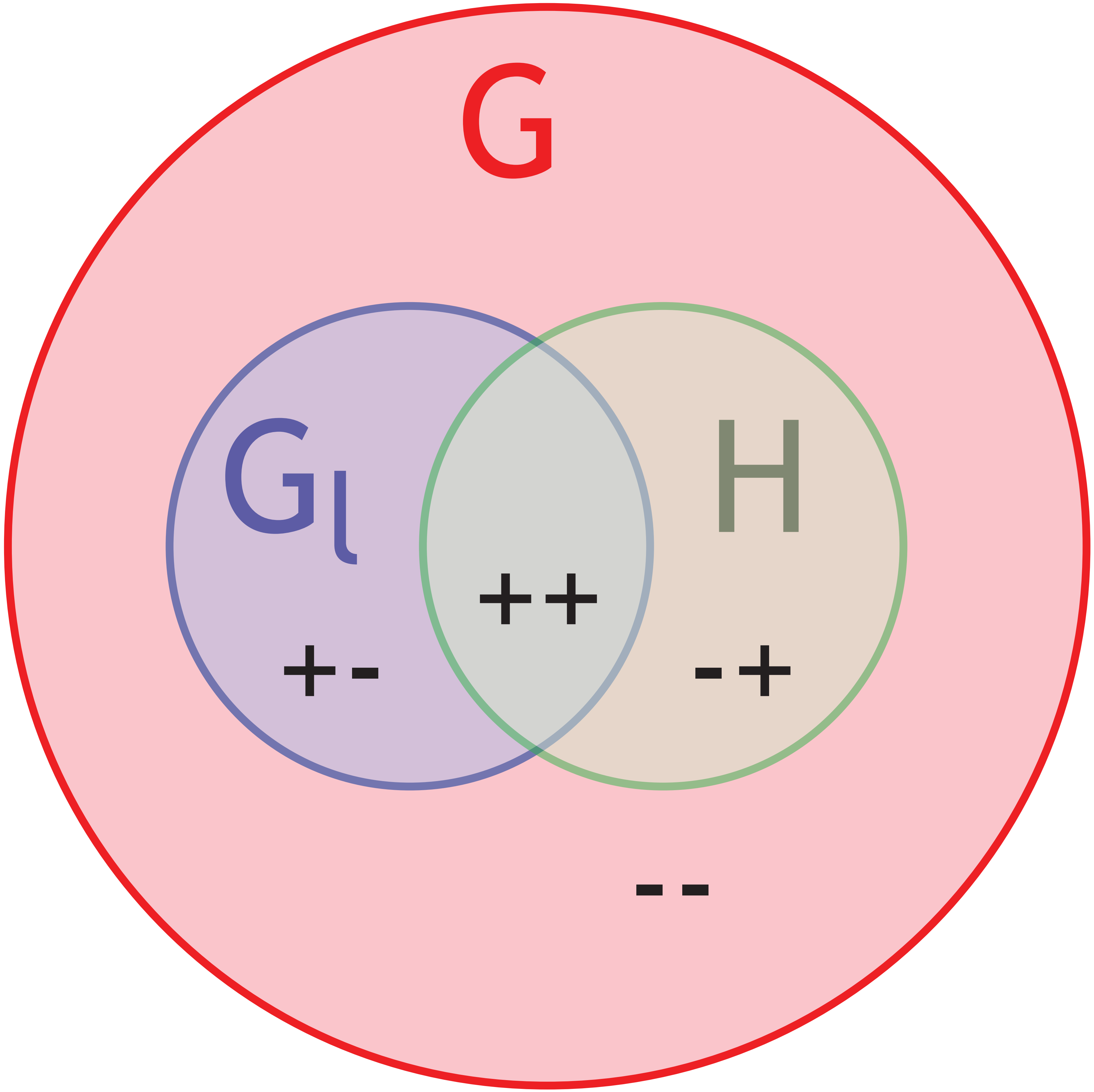
boundary conditions at z_0 , z_R

$$\begin{array}{lcl} \text{Neumann} & + & \partial_5 A_m^A = 0 \\ \text{Dirichlet} & - & A_m^A = 0 \end{array}$$

whatever the b.c. of A_m^A , A_5^A has the opposite b.c.

$+ \quad +$ for A_m^A implies zero mode in A_m^A
(unbroken gauge symmetry)

$- \quad -$ for A_m^A implies zero mode in A_5^A
(Goldstone boson)


G
Gl
H
+-
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Realization of fermions:

$$\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

A mass term in allowed in 5-d: $c = m/k$

$\pm$ b.c. for ψ_L implies $\mp$ b.c. for ψ_R

so

$+ \quad +$ zero mode of ψ_L

$- \quad -$ zero mode of ψ_R

Shapes of the zero modes:

$$|\psi_{L0}|^2 \sim \int \frac{dz}{z} z^{1-2c} \qquad |\psi_{R0}|^2 \sim \int \frac{dz}{z} z^{1+2c}$$

so

	$c < -1/2$	$-1/2 < c < 1/2$	$1/2 < c$
ψ_{L0}	IR	IR	UV
ψ_{R0}	UV	IR	IR

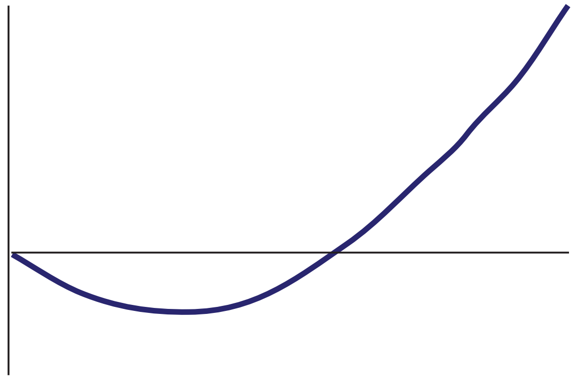
$A_{50}^{A} \sim z^1$, so IR zero modes are needed for a large contribution to the potential for the Higgs field example of a phase transition:

G = SO(2) $\quad \psi_1 : \begin{pmatrix} + & + \\ - & - \end{pmatrix} \quad \psi_2 : \begin{pmatrix} - & + \\ + & - \end{pmatrix}$

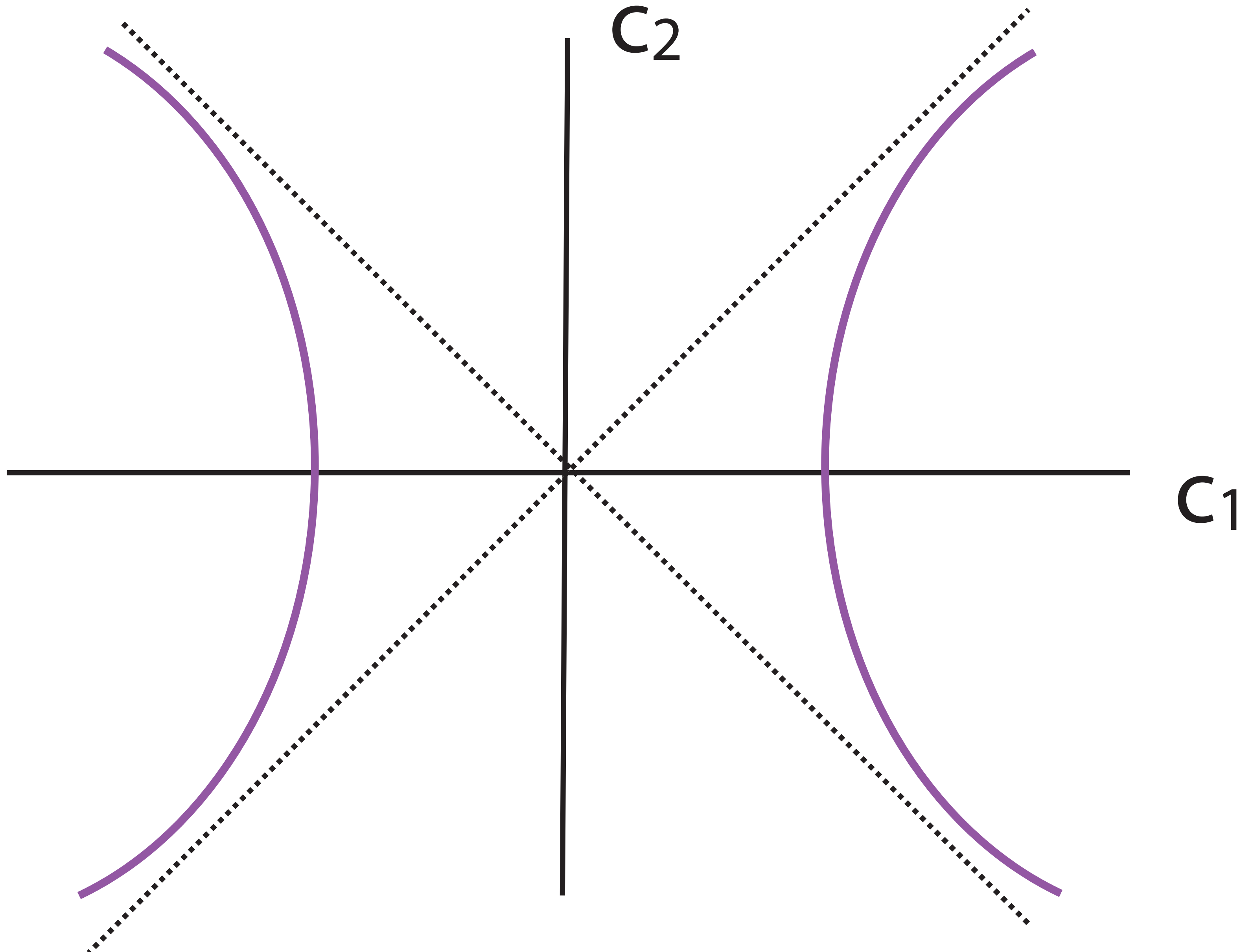
The Coleman-Weinberg potentials are

$$V_1 = -A_1 s^2 + B_1 (s^4 + b s^4 \log \frac{1}{s^2})$$
$$V_2 = +A_2 s^2 + B_2 s^4$$

Near the point $A_1(c_1) \approx A_2(c_2)$, we approach a second order phase transition, and $\langle s \rangle \to 0$



This brings us to a region of small (fine-tuned) v/f .



$$c_1 \sim \pm 0.35 \qquad \text{for} \qquad c_2 = 0$$

Including the gauge field contribution to the Higgs potential makes this story more complex.

However, we must also deal with the fact that the G gauge coupling must be rather large, while the SU(2)xU(1) couplings are small.

Duality tells us to deal with this by adjusting the SU(2)xU(1) couplings at 100 TeV, through boundary contributions on the brane at z_0 .

$$\int d^4x \left(-\frac{1}{4} C_A (F^A_{mn})^2 \right) \Big|_{z_0}$$

This makes the gauge contribution to the Higgs potential for SU(2)xU(1) breaking a small effect.

An example with $G = SO(5) \to H = SO(4)$

with 5-d fermions in the **5** of $SO(5)$. $c = 0.5$

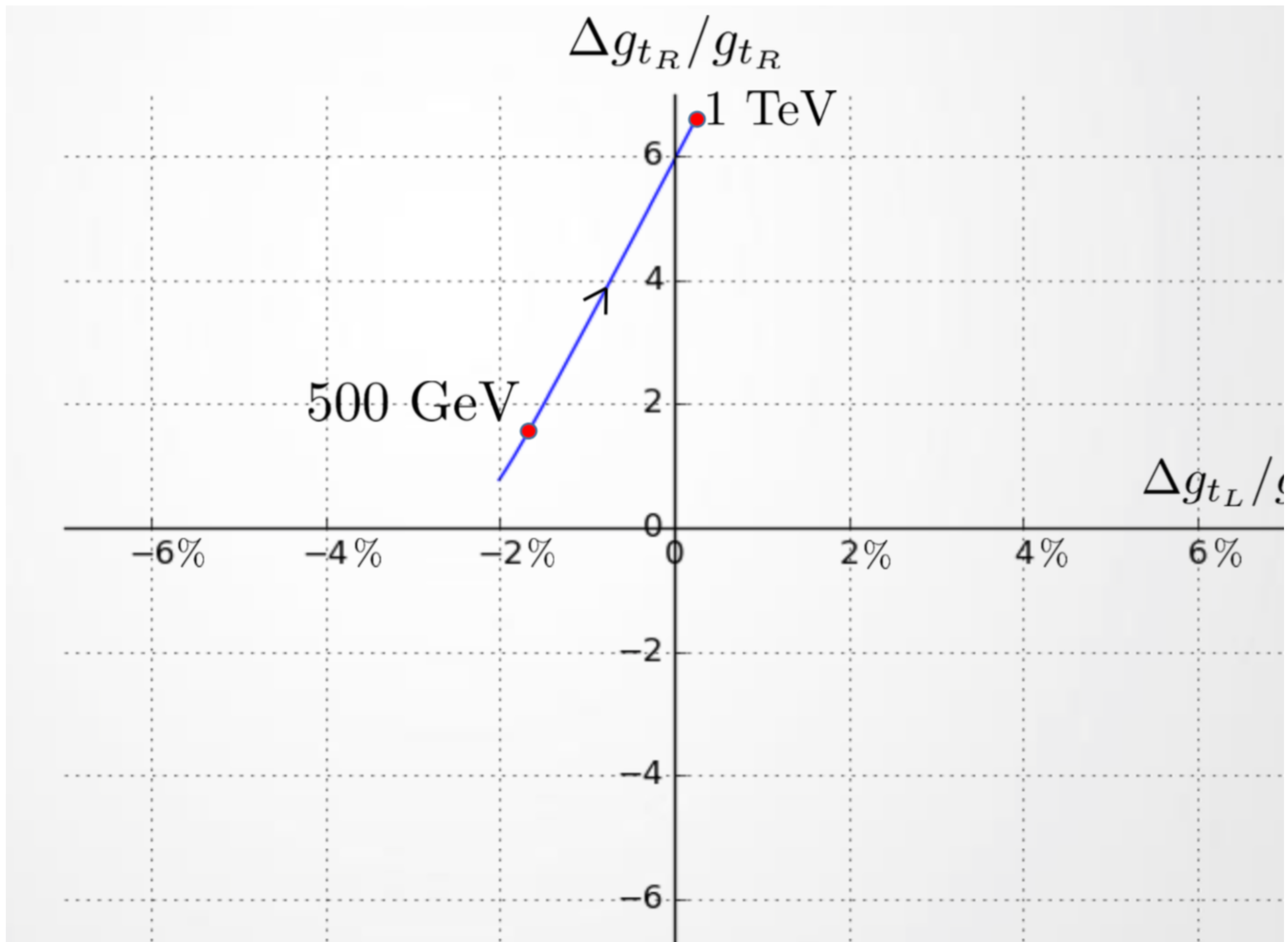
$$\Psi_1 = \begin{pmatrix} - & + \\ + & + \\ + & + \\ - & + \\ - & - \end{pmatrix} \begin{array}{c} \\ b_L \\ t_L \\ \\ t_R \end{array} \qquad \Psi_2 = \begin{pmatrix} - & + \\ - & + \\ + & - \\ - & + \\ - & + \end{pmatrix} \begin{array}{c} \\ \\ T_L \\ \\ T_R \end{array}$$

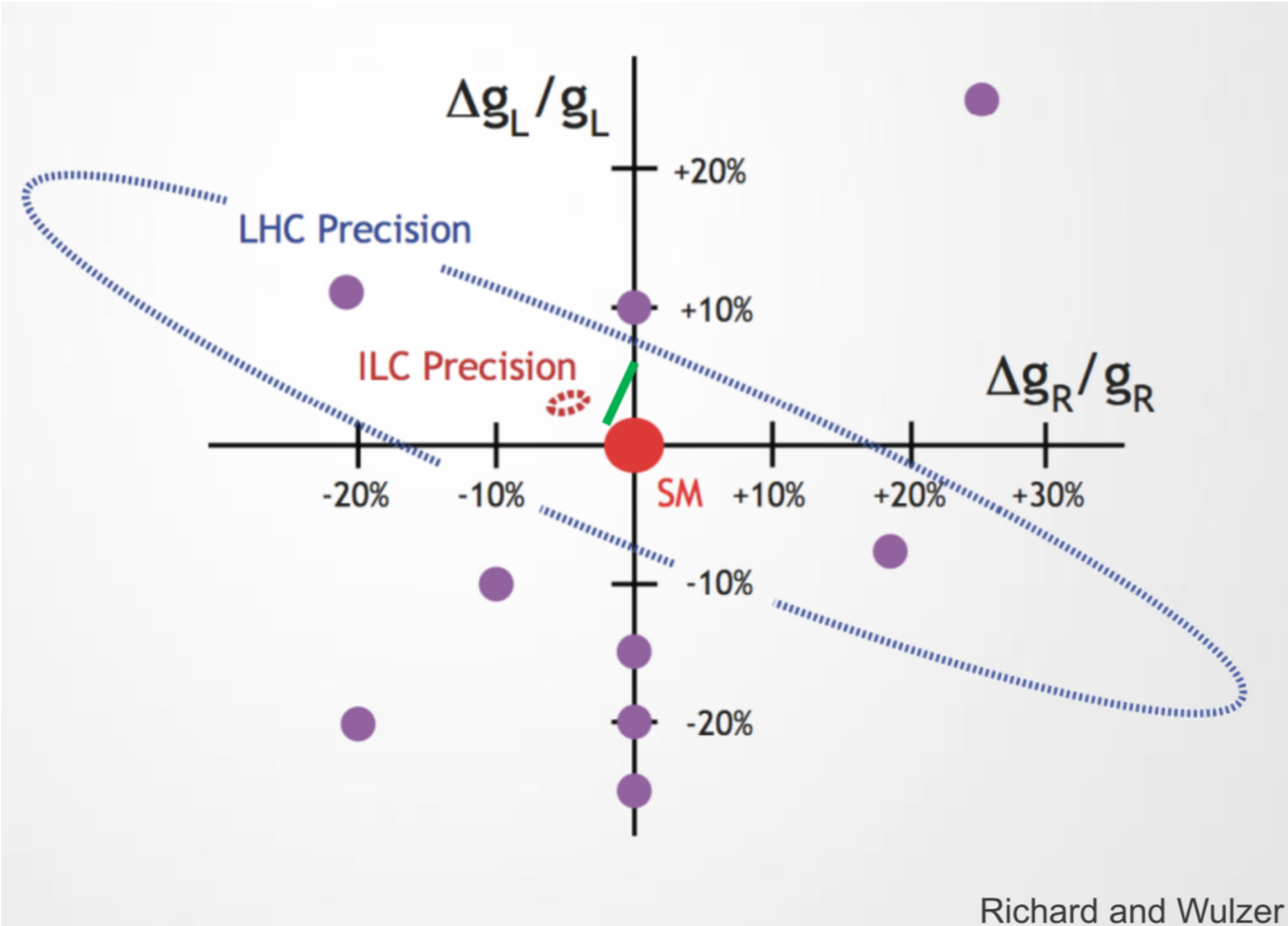
with $c_1 \sim 0.5$ $c_2 \sim 0.2$

Note that at $c = 0.5$, L zero modes decouple from KK excitations. This relieves the constraint from $\Gamma(Z \to b\bar{b})$

What about the top quark couplings ?

Yoon found a parameter point, consistent with all current constraints, with a smaller effect than previous estimates.




$\Delta g_L / g_L$
+20%
LHC Precision
+10%
ILC Precision
$\Delta g_R / g_R$
-20%
-10%
SM
+10%
+20%
+30%
-10%
-20%
Richard and Wulzer

Yoon and I are still trying to understand the global parameter space that follows from these new model-building techniques.

We hope to report more global results soon.