Non-SUSY BSM: Lecture 2/2

Models

Benasque September 26, 2013

Mariano Quirós

ICREA/IFAE

Introduction

A given model in 5D is defined by:

- A specific gravitational background: flat, warped,...
- The gauge and global symmetries (this is as in 4D models)
- Specifying the field content (as in 4D models): e.g. the SM field content or extensions thereof
- Specifying the fields propagating in the bulk and fields localized on various branes
- Specifying the 5D parameters: e.g. 5D Dirac masses

The procedure to establish connection with experiment is:

- To perform KK decomposition for bulk fields
- To compare with existing data
  - Electroweak precision and flavor constraints
  - Direct collider bounds
- To make predictions

Outline

The outline of this lecture is

- The 5D SM
- Electroweak precision observables
  - General expressions
  - Holographic methods
- Flat extra dimensions: UED
- AdS_5 a.k.a. RS
  - The hierarchy problem
  - Anarchy: flavour theory
  - EW constraints
- Relaxing the EWPT
  - Non-custodial models in warped dimension
  - Custodial models

The 5D SM

- We will now consider the Standard Model (SM) propagating in a 5D space with an arbitrary metric $A(y)$ such that in proper coordinates [1]

$$ds^2 = e^{-2A(y)} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2 \,,$$

- We define the 5D $SU(2)_L \times U(1)_Y$ gauge bosons as $W^i_M(x,y)$, $B_M(x,y)$ [or in the weak basis $A^\gamma_M(x,y)$, $Z_M(x,y)$ and $W^\pm_M(x,y)$]
- The SM Higgs

$$H(x,y) = \frac{1}{\sqrt{2}} e^{i\chi(x,y)} \left(\begin{array}{c} 0 \\ h(y) + \xi(x,y) \end{array} \right)$$

  where the matrix $\chi(x,y)$ contains the three 5D SM fields $\vec{\chi}(x,y)\vec{\sigma}$
- The Higgs background $h(y)$ as well as the metric $A(y)$ are arbitrary functions

[1] Note that $\eta_{\mu\nu} = (1,-1,-1,-1)$

- We will consider the 5D action for the gauge and Higgs fields

$$S_5 = \int d^4x dy \sqrt{g} \left(-\frac{1}{4} \vec{W}_{MN}^2 - \frac{1}{4} B_{MN}^2 + |D_M H|^2 - V(H) \right) - \sum_\alpha \int d^4x dy \sqrt{-\bar{g}_\alpha}\, (-1)^\alpha\, 2\, \lambda^\alpha(H)\; \delta(y - y_\alpha)$$

- From here on we will assume that $V(H)$ is quadratic in H and EWSB is triggered on the IR brane
- We thus choose the brane potentials as

$$\lambda^0(\phi_0, H) = M_0 |H|^2 \,, \quad -\lambda^1(\phi_1, H) = -M_1 |H|^2 + \gamma |H|^4$$

- One can then construct the 4D effective theory by making the KK-mode expansion

$$A_\mu(x,y) = \sum_n A_\mu^n(x) \cdot f_A^n(y)/\sqrt{y_1}, \quad A = A^\gamma, Z, W^\pm$$

- The functions f_A satisfy the EOM, normalization conditions and (+,+) BC's

$$m_{f_A}^2 f_A + (e^{-2A} f_A')' - M_A^2 f_A = 0, \quad f_A'\big|_{y=0,y_1} = 0$$

$$\int_0^{y_1} f_A^2(y) dy = y_1$$

- We have introduced EWSB in the mass spectrum and defined the 5D y-dependent gauge boson masses as

$$M_W(y) = \frac{g_5}{2} h(y) e^{-A(y)}, \quad M_Z(y) = \frac{1}{c_W} M_W(y), \quad M_\gamma(y)$$

where $c_W = g_5/\sqrt{g_5^2 + g_5'^2}$, and g_5 and g_5' are the 5D $SU(2)_L$ and $U(1)_Y$ couplings respectively

- Only the lightest mass eigenvalue will be significantly affected by the breaking so we simplify our notation by defining

$$m_A = m_{f_A^0}\,,$$

for the zero modes and

$$m_n = m_{f_A^n}\,, \qquad f^n = f_A^n\,,$$

for the higher modes ($n \geq 1$).

- In particular masses and wave functions of the $n \geq 1$ KK excitations of the W and Z bosons as well as photon and gluons (almost) coincide
- The masses of light modes ($n = 0$) m_Z and m_W have to be matched to the physical values. An approximated expression is given by

$$m_A^2 \approx m_{A,0}^2 \equiv \frac{1}{y_1}\int_0^{y_1} dy\, M_A^2(y)$$

- In case the lightest mode after electroweak breaking is separated by a gap from the KK spectrum the expansion in powers of $m^2_{A,0}$ can be carried out analogously for its wave function
- It turns out that

$$f_A^0(y) = 1 + \delta_A - \delta f_A(y)$$

$$\delta f_A(y) = -m^2_{A,0} y_1 \int_0^y e^{2A} \left(\Omega - \frac{y'}{y_1} \right)$$

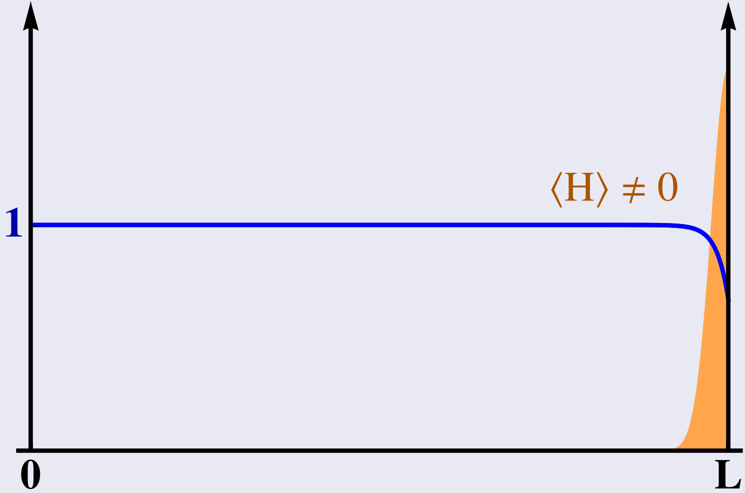
$$\delta_A = -m^2_{A,0} y_1 \int_0^{y_1} e^{2A} \left(\Omega - \frac{y'}{y_1} \right) \left(1 - \frac{y'}{y_1} \right)$$

where the function Ω

$$\Omega(y) = \frac{\int_0^y h^2(y') e^{-2A(y')}}{\int_0^{y_1} h^2(y') e^{-2A(y')}}$$

- In the case of an IR brane localized Higgs it is actually a step function: in the bulk $\Omega = 0$ and $\Omega(y_1) = 1$

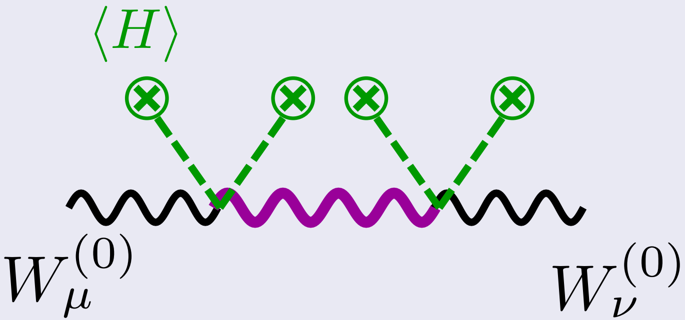
The zero mode is no longer flat



Electroweak precision observables

- One has to check that the SM properties are not distorted too much by the new physics (i.e. by the KK-modes).
- Given that these are *decoupling* effects, this can be used to set a lower bound on the KK scale.
- The most sensitive and robust constraints are derived from the EW precision measurements
- Generically, the largest deviations from SM properties arise from the fact that when the 0-mode Higgs, that by assumption has an IR-brane localized profile (perhaps δ-function), acquires a vacuum expectation value, it adds a y-dependent mass to the gauge EOM
- The would-be 0-mode wavefunction is modified near the IR brane, as illustrated in the previous figure
- The dominant source of constraints arises from the requirement to fulfill the relation $M_W^2 = M_Z^2 \cos^2\theta_w$, which is observed to hold to excellent accuracy and suggests the existence of a *custodial symmetry*: $\rho - 1 \equiv \alpha T$

- When we embed the SM into a warped extra dimension there are tree-level violations of custodial invariance proportional to g'



- Wavy internal line is propagation of KK modes
- The way to suppress them is by increasing the KK masses

General expressions

- There are three experimental input parameters usually referred as Peskin-Takeuchi (S, T, U) parameters
- However the U parameter is expected to be small since it corresponds to a dimension eight operator
- On the other hand, there are dimension six operators which in some models can have sizable coefficients
- It has thus been suggested to instead consider the set T, S, Y and W as a more adequate basis for models of new physics

$$\alpha T = m_W^{-2}\left[c_W^2 \Pi_Z(0) - \Pi_W(0)\right]$$

$$\alpha S = 4 s_W^2 c_W^2 \left[\Pi_\gamma'(0) - \Pi_Z'(0)\right]$$

$$2 m_W^{-2} Y = s_W^2 \Pi_Z''(0) + c_W^2 \Pi_\gamma''(0)$$

$$2 m_W^{-2} W = c_W^2 \Pi_Z''(0) + s_W^2 \Pi_\gamma''(0)$$

- α is the electromagnetic gauge coupling defined at the Z-pole mass
- The 4D gauge couplings are defined as $g^2 = g_5^2/y_1$ and $g'^2 = g_5'^2/y_1$
- In theories with a Higgs mode H of mass $m_H \ll m_{\rm KK}$ one can relate T, S, Y, and W to the coefficients of the dimension six operators

$$|H^\dagger D_\mu H|^2\,, \quad H^\dagger W_{\mu\nu} H B^{\mu\nu}\,, \quad (\partial_\rho B_{\mu\nu})^2\,, \quad (D_\rho W_{\mu\nu})^2$$

- T (four Higgs insertions) and S (two Higgs insertions) are related to EWSB
- Y and W are unrelated to EWSB
- In the following we will assume fermions localized on the UV brane (first and second generation fermions)
- We have to worry then for the brane-to-brane gauge boson propagators
- The simplest technique uses holographic methods

Holographic methods

- In order to compute the brane-to brane propagator, let us define the quantity

$$P(y, p^2, m_{A,0}^2) = e^{-2A(y)} \frac{f_A'(p^2, y)}{f_A(p^2, y)} ,$$

- The holographic profile $f_A(p^2, y)$ satisfies the EOM

$$\left(e^{-2A} f_A'(p^2, y)\right)' = (M_A^2 - p^2) f_A(p^2, y) .$$

- From this it follows that P satisfies the differential equation and boundary condition

$$P' + e^{2A} P^2 = -p^2 + m_{A,0}^2 \omega(y) , \quad P(y_1, p^2, m_{A,0}^2) = 0 , \quad \omega(y) = \frac{M_A^2(y)}{m_{A,0}^2}$$

- We will solve for P in a series expansion in powers of p^2 and $m_{A,0}^2$
- Matching order by order one finds (the subindex denotes the order of both p^2 and $m_{A,0}^2$)

$$P_0' + e^{2A} P_0^2 = 0$$

$$P_1' + 2e^{2A} P_0 P_1 = -p^2 + m_{A,0}^2 \omega$$

$$P_2' + e^{2A}(P_1^2 + 2P_0 P_2) = 0$$

- Enforcing now the boundary condition at each order one easily finds the solution

$$P_0 = 0$$

$$P_1 = p^2(y_1 - y) - m_{A,0}^2 y_1 (1 - \Omega)$$

$$P_2 = \int_y^{y_1} e^{2A} \left[-p^2(y_1 - y') + m_{A,0}^2 y_1 (1 - \Omega)\right]^2$$

- The inverse brane-to-brane propagator in the holographic picture is

$$A_\mu(p,0) = f_A(p^2,0)\bar{A}_\mu(p) \quad \Longrightarrow \quad \Pi_A(p^2) = \frac{1}{y_1} P(0,p^2,m_{A,0}^2)$$

- Finally

$$\Pi_A(p^2) = p^2 - m_{A,0}^2 + y_1 \int_0^{y_1} e^{2A}\left[-p^2\left(1-\frac{y}{y_1}\right) + m_{A,0}^2(1-\Omega)\right]^2 + \dots,$$

$$\alpha T = s_W^2 m_Z^2 y_1 \int e^{2A}(1-\Omega)^2$$

$$\alpha S = 8 s_W^2 c_W^2 m_Z^2 \int e^{2A}\,(y_1-y)\,(1-\Omega)$$

$$Y = W = \frac{c_W^2 m_Z^2}{y_1}\int e^{2A}\,(y_1-y)^2$$

Flat extra dimensions

- This is the simplest case, where $A(y) = 0$
- Gauge fields propagate in the bulk
- If all matter fields propagate in the bulk the setup is dubbed:

Universal Extra Dimensions (UED)

- All KK equations reduce to the simple harmonic oscillator equation

$$f_n'' + m_n^2 f_n = 0, \quad y_1 = \pi R, \quad m_n = \frac{n}{R}, \quad \text{forget EWSB}$$

$$f_n^{(+,+)} = \begin{cases} 1 & \text{for} \quad n = 0 \\ \sqrt{2}\cos\frac{ny}{R} & \text{for} \quad n \neq 0 \end{cases}, \quad \text{or} \quad f_n^{(-,-)} = \sqrt{2}\sin\frac{ny}{R}$$

$$\frac{1}{\pi R}\int_0^{\pi R} dy\, f_m^{(+,+)} f_n^{(+,+)} = \delta_{mn}, \quad \text{and} \quad \frac{1}{\pi R}\int_0^{\pi R} dy\, f_m^{(-,-)} f_n^{(-,-)} = \delta_{mn}$$

- As the wave functions are sines and cosines there is a very simple selection rule. For instance

$$\frac{1}{\pi R}\int_0^{\pi R} dy\, f_{n_1}^{(+,+)} f_{n_2}^{(+,+)} f_{n_3}^{(+,+)} =$$

$$\frac{1}{\sqrt{2}\pi}\left\{\frac{\sin(n_1+n_2+n_3)\pi}{n_1+n_2+n_3}+\frac{\sin(n_1+n_2-n_3)\pi}{n_1+n_2-n_3}\right.$$

$$\left.+\frac{\sin(n_1-n_2+n_3)\pi}{n_1-n_2+n_3}+\frac{\sin(n_1-n_2-n_3)\pi}{n_1-n_2-n_3}\right\}$$

- Since n_1, n_2, n_3 are integers the integral vanishes unless: either $n_1+n_2+n_3=0$, or $n_1+n_2-n_3=0$, or $n_1-n_2+n_3=0$, or $n_1-n_2-n_3=0$
- The general selection rule is that

$$n_1 \pm n_2 \pm \cdots \pm n_N = 0$$

provided there is an even number of $f_n^{(-,-)}$ insertions

- This is the case as for instance the Yukawa couplings in the bulk are

$$H\overline{Q}U = \underset{(+,+)}{H}\underset{(+,+)}{\overline{Q}_L}\underset{(+,+)}{U_R} + \underset{(+,+)}{H}\underset{(-,-)}{\overline{Q}_R}\underset{(-,-)}{U_L}$$

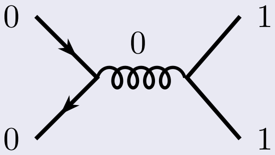
- The bulk theory above has an exact discrete symmetry under which

KK-Parity

$$\phi_n \mapsto (-1)^n \phi_n \qquad \text{where } \phi = A_\mu, \psi, H$$

- KK-parity has important phenomenological consequences

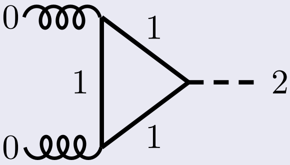
$\mathcal{A}(00 \to 0 \to 11) \neq 0$: $n = 1$ modes are not singly produced



Difficult Direct Detection

- Even KK modes are allowed only at loop level (suppressed)

Only $n = 2$ can be singly produced: loop suppressed



Difficult Direct Detection

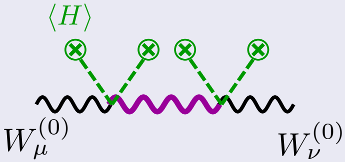
- Odd (i.e. n=1) KK modes cannot be produced by Drell-Yan processes at LHC for external n=0 modes

$$\mathcal{A}(00 \to 1 \to 00) = 0$$

$$\Updownarrow$$

Difficult Direct Detection

- As for electroweak observables the relation between m_W and m_Z is produced by the mixing between W^3_μ and B_μ. In general there can be a mixing at the level of KK-modes between $W^{3(0)}_\mu$ and $B^{(n)}_\mu$ giving rise to a modification of the mass ratio m_W/m_Z as in



- Because of KK-parity there is no such tree-level mixing and

KK-modes only affect electroweak observables at loop level

- Finally

THE LIGHTEST $n = 1$ STATE IS EXACTLY STABLE WHICH LEADS TO A WIMP DARK MATTER CANDIDATE

AdS_5

- This case is determined by the RS metric

$$A(y) = k\, y$$

- The wave equations reduce to Bessel functions

Scalars with $M^2 = (\alpha^2 - 4)k^2$

$$\text{EOM:}\quad f_n'' - 2kf_n' + \left[(1-\alpha^2)k^2 + m_n^2 e^{2ky}\right] f_n = 0$$

$$\text{Solution:}\quad f_n = N_n\, e^{ky}\left\{J_\alpha\left(\frac{m_n}{k}\, e^{ky}\right) + b_n\, Y_\alpha\left(\frac{m_n}{k}\, e^{ky}\right)\right\}$$

$$\text{Normalization} \quad\Longrightarrow\quad N_n$$

$$\text{IR BC} \quad\Longrightarrow\quad b_n$$

$$\text{UV BC} \quad\Longrightarrow\quad m_n$$

Fermions with $M = \pm ck$ with $\pm$ BC's

$$\text{EOM:} \quad (f^n_{L,R})' + (c - \frac{1}{2})k\, f^n_{L,R} = \pm m_n e^{ky} f_{R,L}$$

$$\text{BC:} \quad (f^n_{L,R})' + (c - \frac{1}{2})k\, f^n_{L,R}\Big|_{y=y_\alpha} = 0, \quad f_{R,L}\big|_{y=y_\alpha} = 0$$

$$\text{Solution:} \quad f^n_{L,R} = N_n\, e^{ky} \left\{ J_{c\pm\frac{1}{2}}\left(\frac{m_n}{k}\, e^{ky}\right) + b_n\, Y_{c\pm\frac{1}{2}}\left(\frac{m_n}{k}\, e^{ky}\right) \right\}$$

$$\text{Normalization} \quad \Longrightarrow \quad N_n$$

$$\text{IR BC} \quad \Longrightarrow \quad b_n$$

$$\text{UV BC} \quad \Longrightarrow \quad m_n$$

Gauge bosons (limit of $EWSB \to 0$) with (N,N) BC's

$$\text{Solution:} \quad f^n = N_n\, e^{ky} \left\{ J_1\left(\frac{m_n}{k}\, e^{ky}\right) + b_n\, Y_1\left(\frac{m_n}{k}\, e^{ky}\right) \right\}$$

- The 5D Einstein-Hilbert action takes the form

$$\mathcal{R}_5[g] = e^{2A}\mathcal{R}_4[g_4]$$

$$S = -\frac{1}{2}\int d^5x\sqrt{g}M_5^3\mathcal{R}_5[g] = -\frac{1}{2}\int d^4x\sqrt{g_4}M_5^3\int_0^{y_1} dy e^{-2A}\mathcal{R}_4[g_4]$$

- Which identifies the 4D Planck mass as

$$M_P^2 = M_5^3\int_0^{y_1} dy e^{-2A} = \frac{M_5^3}{2k}\left(1 - e^{-2ky_1}\right)$$

- The warp factor ky_1 is such that Planck-sized scales are warped down to TeV scales in the IR brane

$$e^{-ky_1}M_P \sim \mathcal{O}(TeV) \quad \Longrightarrow ky_1 \sim 35$$

$$M_P^2 \simeq M_5^3/2k$$

The hierarchy problem

- If we define the Higgs mass in the bulk

$$V(H) = M^2|H|^2, \quad M^2 = a(a-4)k^2$$

- The EOM and BC's are (see Lecture 1): "not the physical one"

$$h'' - 4A'h' - M^2 h = 0, \quad h'(y_\alpha) = \left.\frac{\partial \lambda^\alpha}{\partial h}\right|_{y=y_\alpha}$$

- The solution is given by

$$h(y) = c_1 e^{aky} + c_2 e^{(4-a)ky} \begin{cases} \sim c_1\, e^{aky} & \text{for } a > 2 \\ \sim c_2 e^{(4-a)ky} & \text{for } a < 2 \end{cases}$$

- In the holographic picture

$$a \equiv dim(\mathcal{O}_H)$$

- Then for $a \geq 2$

$$h(y) = c_1 e^{aky} \quad \text{unless we fine tune } c_1 \equiv 0 \quad \Longrightarrow h(y) = c_2 e^{(4-a)ky}$$

- For $a < 2$

$$h(y) = c_2 e^{(4-a)ky} \quad \text{unless we fine tune } c_2 \equiv 0 \quad \Longrightarrow h(y) = c_1 e^{aky}$$

- In all cases no fine tuning implies that

$$a = 2 + \Delta \quad \Longrightarrow h(y) \simeq e^{(2+|\Delta|)ky} \quad \text{or} \quad h(y) \simeq e^{aky} \text{with } a > 2$$

- The hierarchy problem is solved in the holographic picture if

$$dim(\mathcal{O}_H) \geq 2$$

Flavor anarchy

- The freedom to localize the fermion 0-modes offers an appealing understanding of the observed fermion mass hierarchies
- In 5D, a bulk Yukawa operator leads to

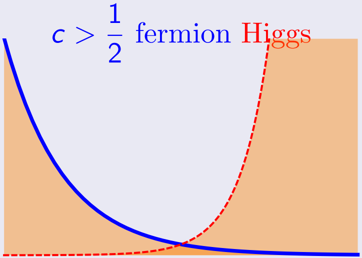
$$y_5 H \overline{\Psi}_1 \Psi_2 + \text{h.c.} \Longrightarrow y_4 v \bar{\psi}^0_{1L} \psi^0_{2R} + \text{h.c.} + \text{“KK-modes”}$$

where

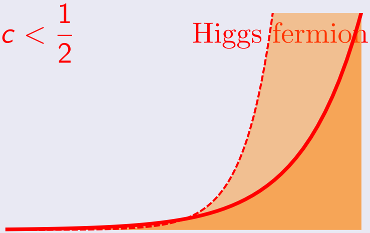
$$y_4 = \left(\frac{y_5}{\sqrt{y_1}} \right) \frac{1}{y_1} \int_0^{y_1} dy\, h(y) f^0_{\psi_1}(y) f^0_{\psi_2}(y)$$

- Thus, the 4D Yukawa couplings depend not only on the 5D Yukawa couplings, but also on the fermion localization
- The assumption of *flavor anarchy* in this context corresponds to taking the 5D Yukawa matrices to be generic matrices
- The hierarchical structure of the observed fermion masses (and mixing angles) would be a consequence of the fermion geography

Light fermions



Heavy fermions



We have randomly generated a set of 40,000 complex 5D Yukawas and fitted the 9 parameters c_ψ

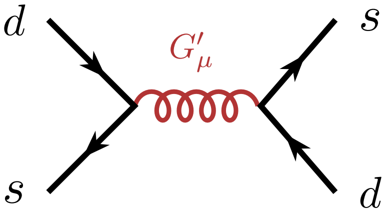
The result of the fit (including 1σ)

$c_{(u,d)L} = 0.66 \pm 0.02$	$c_{(c,s)L} = 0.59 \pm 0.02$	$c_{(t,b)L} = -0.11^{+0.45}_{-0.53}$
$c_{uR} = 0.71 \pm 0.02$	$c_{cR} = 0.57 \pm 0.02$	$c_{tR} = 0.42^{+0.05}_{-0.17}$
$c_{dR} = 0.66 \pm 0.03$	$c_{sR} = 0.65 \pm 0.03$	$c_{bR} = 0.64 \pm 0.02$

- One should point out that there are *tree-level* FCNC effects arising from the fact that the light families are not localized in *exactly* the same way
- This means that there is some flavor-dependence in the couplings of the fermions to KK gluons as

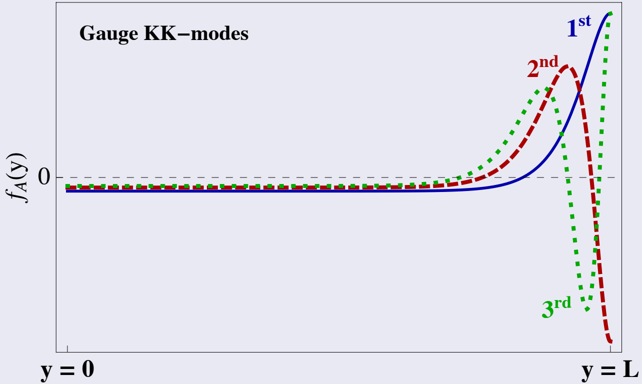
$$g_{F_iF_jG} = \left(\frac{g_5}{\sqrt{y_1}}\right)\frac{1}{y_1}\int_0^{y_1} dy\, f^0_{F_i}(y) f^0_{F_j}(y) f_{G^{(1)}}(y)\ ,$$

- Although $g_{F_iF_jG}$ is diagonal in the fermion gauge eigenbasis, the fact that they are fermion-dependent (through the c-dependence), means that in the mass eigenbasis, off diagonal couplings are induced



$K^0 - \bar{K}^0$oscillations: Δm_K^2

- However the gluon KK mode es very flat at the UV brane (towards where the light fermions are localized)



- This leads to suppressed flavor changing KK-gluon vertices: known as the RS-GIM mechanism

Electroweak constraints

- The T and S parameters can be readily computed from general expressions yielding

$$\alpha(m_Z)T_{RS} = s_W^2 \frac{m_Z^2}{\rho^2}(ky_1)\frac{(a-1)^2}{a(2a-1)} + \ldots$$

$$\alpha(m_Z)S_{RS} = 2s_W^2 c_W^2 \frac{m_Z^2}{\rho^2}\frac{a^2-1}{a^2} + \ldots \quad m_{KK} \simeq 2.4\rho$$

  where the ellipses indicate subleading corrections in the large volume ky_1 and $\rho = k\exp(-ky_1) \sim$ TeV
- T parameter is volume enhanced: strong constraints
- Using the experimental values $T = 0.07 \pm 0.08, \quad S = 0.03 \pm 0.09,$

$$\begin{cases} a \to \infty \text{ (localized Higgs)} & m_{KK} > 10.4 \text{ TeV} \\ a = 2 & m_{KK} > 6 \text{ TeV} \end{cases}$$

Relaxing EWPT

- The large values on lower bounds on KK modes make the simple RS model
  - Uninteresting from the experimental side as there is no hope to detect KK modes at the LHC
  - Uninteresting from the theoretical side as it creates a little hierarchy problem between the EW scale and the KK scale
- There are essentially two ways of improving the behaviour of electroweak observables
  - One way is to keep the gauge structure but modify the gravitational metric:

From $AdS_5 \Longrightarrow$ Asymptotically AdS_5

  - Another way is modifying the gauge structure to incorporate the custodial symmetry as a gauge symmetry in the 5D setup

Deformed metric

- One possibility for deforming the gravitational metric was already discussed in Lecture 1 where we considered

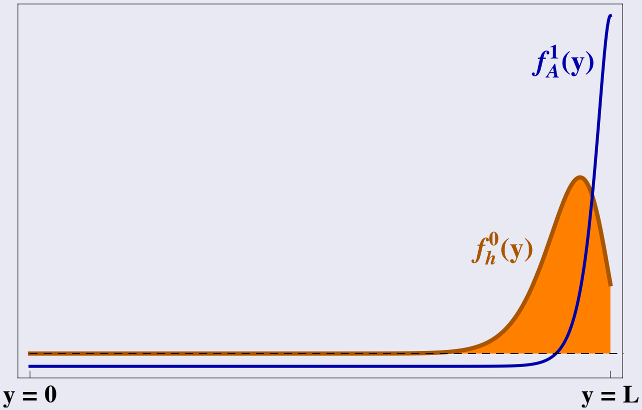
$$A(y) = ky - \frac{1}{\nu^2} \log\left(1 - \frac{y}{y_s}\right)$$

where the singularity lies beyond the IR brane y_1

- Except close to the IR brane $A(y)$ is nearly linear which corresponds to the AdS_5 limit
- The nearby presence of the singularity modifies the background around the IR brane which in turn affects the various wave functions
- In particular the *physical* Higgs wave function is

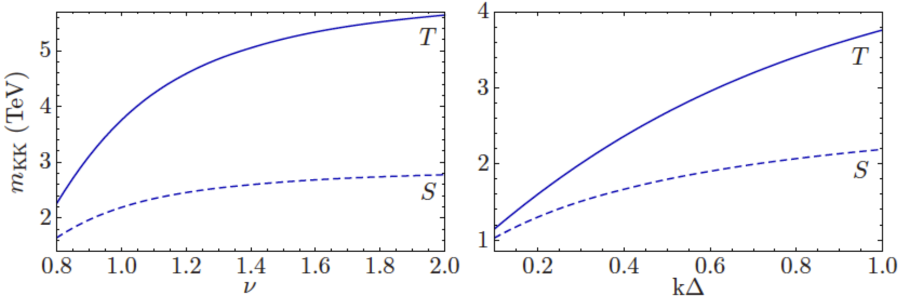
$$f_h(y) = N_h e^{-A(y)} e^{aky} \to 0 \text{ for } y \to y_1 \lesssim y_s, \quad \frac{1}{y_1}\int_0^{y_1} dy f_h^2(y) = 1$$

- As the KK modes are localized towards y_1 the overlap integrals of gauge KK modes with the Higgs are suppressed



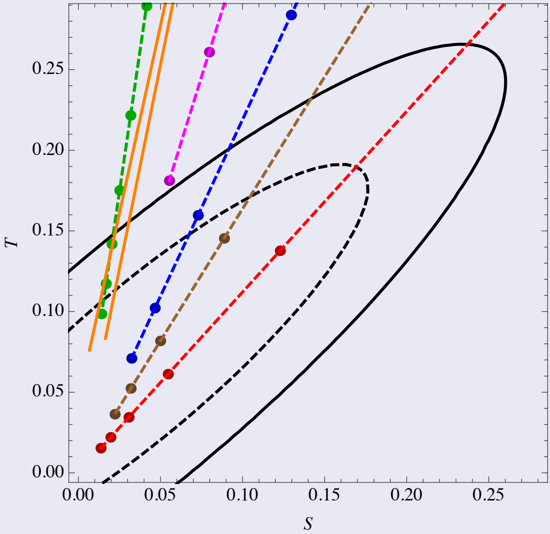
- As a result the constraints from electroweak observables are milder

$a = 2$. Left panel: $k(y_s - y_1) = 1$; Right panel: $\nu = 1$ (95% CL bounds)



- In the limit $\nu \to \infty$ and/or $k(y_s - y_1) \to \infty$ the results go to the RS bounds

$a = 3.1$, $\nu = 0.5, 0.525, 0.55, 0.6$ $m_{KK} \leq 3$ TeV, $\Delta m_{KK} = 0.5$ TeV



Custodial models

- The idea is to introduce a custodial gauged symmetry in the bulk (dual to a 4D model with global custodial symmetry enforced)
- Thus, the SM gauge group is extended to

$$SU(2)_L^{\rm gauge} \times \underbrace{SU(2)_R^{\rm gauge} \times U(1)_X^{\rm gauge}}_{\supset \; U(1)_Y}, \quad (X = B - L), \qquad Y = X + T_R^3$$

- This gauge group is broken by boundary conditions, so that only the SM subgroup has associated massless gauge bosons (before EWSB)
- The LR symmetry remains unbroken on the IR brane, where the strongly interacting states are localized. Thus, the custodial symmetry is exact on this boundary, even for $g' \neq 0$.

Custodial models

- The specific breaking pattern is

$$
\begin{array}{rcll}
W_R^{1,2} & & & (-,+) \\
Z' & = & \frac{1}{\sqrt{g_R^2+g_X^2}}\{g_R W_R^3 - g_X X\} & (-,+) \\
W_L^{1,2,3} & & & (+,+) \\
B_\mu & = & \frac{1}{\sqrt{g_R^2+g_X^2}}\{g_X W_R^3 + g_R X\} & (+,+)
\end{array}
$$

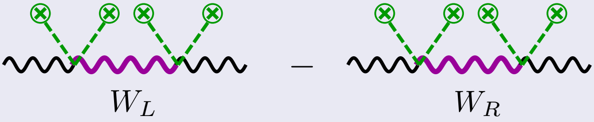
- The LR symmetry remains unbroken in the IR brane.
- The custodial symmetry is exact on the IR brane even for $g' \neq 0$
- In the bulk the T-parameter receives contributions from the massive W_L and W_R fields, leading to a good degree of cancellation, since at the massive level the differences between L and R are small

- Since we are enlarging the bulk gauge symmetry the right-handed fermions should be promoted to doublets under $SU(2)_R$

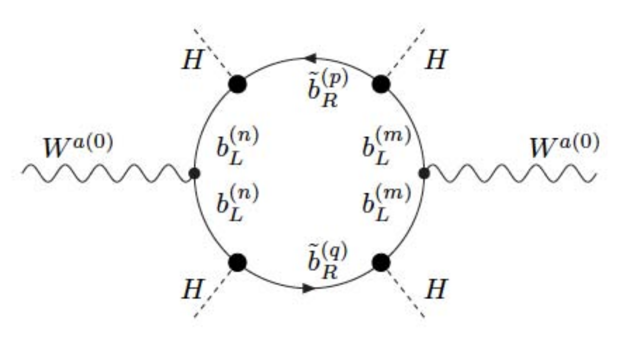
$$Q_{R\,1}=\begin{pmatrix} u_R \\ \tilde{d}_R \end{pmatrix},\quad Q_{R\,2}=\begin{pmatrix} \tilde{u}_R \\ d_R \end{pmatrix},\quad L_R=\begin{pmatrix} e_R \\ \tilde{\nu}_R \end{pmatrix}$$

where only the untilded fields possess a zero mode. Since we are breaking the $SU(2)_R$ through the orbifold BC: one component of $SU(2)_R$ doublet must be even (with zero mode) and the other odd (without zero mode). This doubling on the number of fields is only required in the quark sector as in the lepton sector for the $SU(2)_R$ doublet

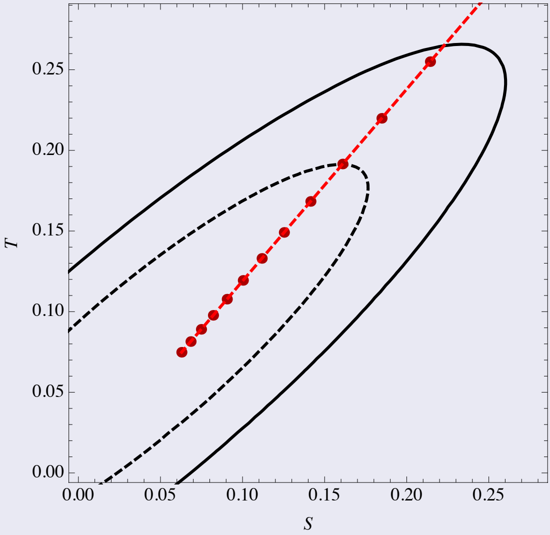
- The contribution from KK modes tends to cancel at tree-level



At the one-loop level, on top of the usual Standard Model leading contribution from the top quark, the dominant contribution comes from a loop where the KK-modes of (t_L, t_R) and $(b_L, \tilde{b}_R)$ are exchanged, as in



$m_{KK} \leq 6$ TeV, $\Delta m_{KK} = 0.25$ TeV; $m_{KK} \gtrsim 3$ TeV, 95% CL



- The Higgs potential and the Higgs mass can also be obtained dynamically by the Coleman-Weinberg mechanism if the Higgs is identified with the fifth component of a 5D gauge boson: Gauge-Higgs-Unification
- GHU is actually an alternative to supersymmetry, where the gauge symmetry in the bulk $\mathcal{G}$ protects the mass of extra-dimensional components of gauge bosons
- This solution to the hierarchy problem requires an extended gauge group with respect to the SM gauge group
- It can be constructed in flat or warped space, although in warped space the GIM-RS mechanism protects the theory with differently localized fermion fields from huge flavor violation, which otherwise would require severe constraints on the mass of KK modes
- The four-dimensional components of 5D gauge bosons (A_μ^a) of $\mathcal{G}$ with (N, N) boundary conditions constitute the four-dimensional gauge bosons while the fifth components ($A_5^{\hat{a}}$), with (N, N) boundary conditions, contain the four-dimensional Higgs fields in a number equal to the number of Pseudo Goldstone Bosons

- In general $\mathcal{G}$ will be broken by boundary conditions to $\mathcal{H}_{UV}$ ($\mathcal{H}_{IR}$) on the UV (IR) brane.
- For $\mathcal{H}_{UV} = SU(2)_L \otimes U(1)_Y$ the number of PGB is $\dim(\mathcal{G}/\mathcal{H}_{IR})$ so different models differ by different choices for $\mathcal{G}$ and $\mathcal{H}_{IR}$.
- Some models are defined in the table below

Model	# Goldstones ($A_5^{\hat{a}}$)
SO(4)/SO(3)	6-3=3 (Higgsless SM)
SU(3)/SU(2)×U(1)	8-4=4(H_{SM})
SO(5)/SO(4)	10-6=4 (H_{SM})
SO(6)/SO(5)	15-10=5 (H_{SM} + singlet)
SO(6)/SO(4)×SO(2)	15-6-1=8 (H_u, H_d)

- The model with $\mathcal{G} = SO(5)$ is a sort of minimal model (MCHM) which contains custodial symmetry on the IR brane and where the Higgs sector=SM Higgs

- In the dual theory $\mathcal{G}/\mathcal{H}_{IR}$ is characterized by the spontaneous breaking scale f_h such that the expansion parameter in the theory is ξ

$$\xi \equiv \left(\frac{v}{f_h}\right)^2 \quad \begin{cases} \bullet \quad \xi \to 0 \Rightarrow \text{SM limit} \\ \bullet \quad \xi \to 1 \Rightarrow \text{Technicolor limit} \end{cases}$$

- The ξ parameter controls perturbative unitarity
- However unlike in the models with a scalar fundamental Higgs, where the parameter $\xi \ll 1$, in the models presented in this section ξ depends on f_h and can thus be considered as a free parameter.
- For instance in the limit $\xi \to 0$ the SM result is obtained and the Higgs unitarizes the theory without the need of any extra particle.
- On the other extreme in the Technicolor limit $\xi \to 1$ all unitarity must be provided by new TeV resonances at scales close to the electroweak scale.
- For intermediate values of $0 < \xi < 1$ unitarity must be partially restored by resonances at scales which depend on the value of ξ.