SM in six dimensional warped geometry[1]

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[1] Under the supervision of Prof. Debajyoti Choudhury

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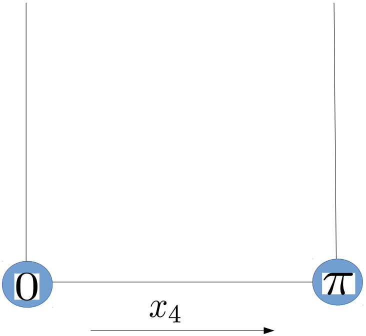

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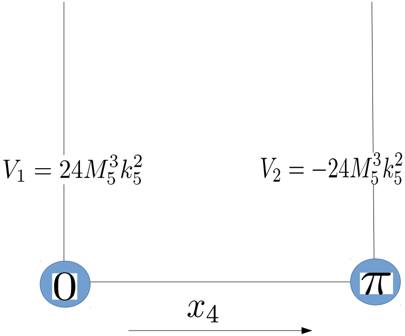

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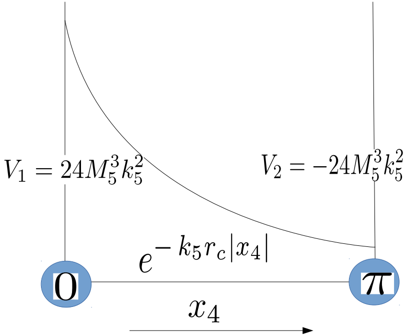

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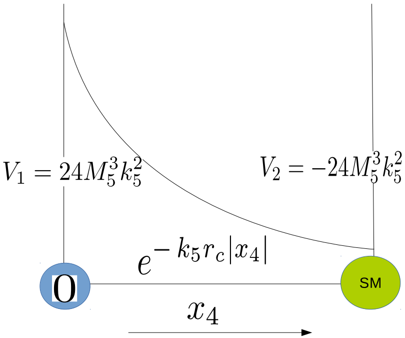

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$$m_H = \widetilde{m}\, e^{-\pi\, k_5\, r_c} \ . \tag{1}$$

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where x_n's are the roots of the Bessel function of order one.
And the coupling of gravitons to $x_4 = \pi$ brane localized matter given by

$$\frac{1}{M_{pl}}\, T^{\mu\nu}_{sm}\, h^0_{\mu\nu}(x_\mu) + \frac{1}{\Lambda_\pi}\, T^{\mu\nu}_{sm}\, h^n_{\mu\nu}(x_\mu)$$

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- main The ATLAS collaboration[2] has ruled out a level–1 KK graviton in the mass range below 1.41 (2.66) TeV for $\frac{k_5}{\bar{M}_{pl}} = 0.01$ (0.1).

$$\frac{m_1}{m_H} = x_1\, \frac{k_5}{M_5}\, \frac{M_5}{\widetilde{m}}\ . \tag{3}$$

for $\frac{k_5}{\bar{M}_{pl}} < 0.1$, leads to $m_1 < 1$ TeV which contradicts the recent lower bound of first RS KK graviton.

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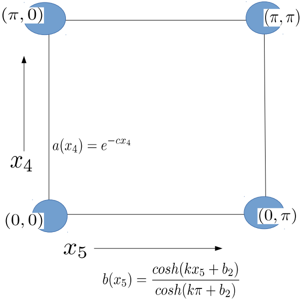

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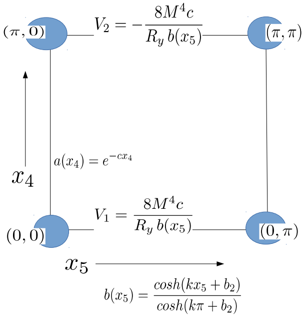

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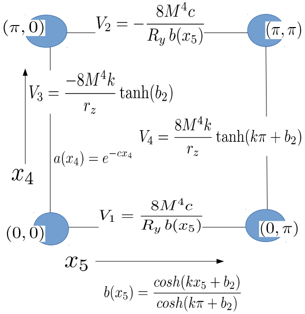

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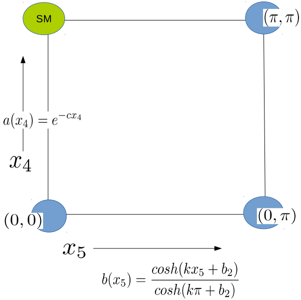

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- **Case 1:** spare Choosing $b_2 = 0$ recovers the results of [5] and we have

$$\begin{aligned} V_1(x_5) &= -V_2(x_5) = \frac{8M^4 k}{r_z}\mathrm{sech}(kx_5)\,, \\ V_3 &= 0 \\ V_4 &= \frac{8M^4 k}{r_z}\tanh(k\pi)\,. \end{aligned} \tag{4}$$

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$$V_1 = -V_2 \approx 0\ , \qquad V_3 \approx \frac{-8M^4 k}{r_z} \approx -V_4 \tag{5}$$

And, $V_3 \approx -V_4$ reveals the near vanishing of the cosmological constant induced on the brane.

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- As for the line element, in this limit,

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Radii Stabilization [7]

- We postulate two scalar fields with one scalar field $\phi_1(x_\mu, x_4, x_5)$, permeating the entire bulk, that would serve to stabilize r_z

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- We intend to carry out this only for Case 2, where $\tilde{\Omega} \rightarrow 0$

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We present $V_{\rm eff}$ for $\phi_1(x_\mu, x_4, x_5)$ (scalar in the bulk) in a graphical form.

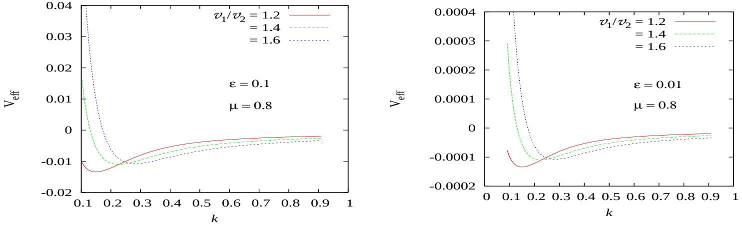

Figure: *The effective potential $V_{eff}(k)$ for different values of the ratio v_2/v_1 of the classical values of the field ϕ on the two constant-x_5 branes. The left (right) panels correspond to $\epsilon = 0.1\,(0.01)$.*

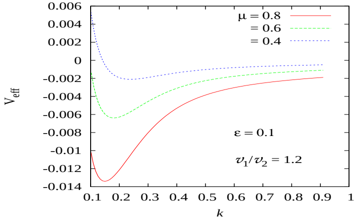

Figure: *The effective potential $V_{eff}(k)$ for different values of the mass of the bulk scalar ϕ_1.*

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where

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- It will be easier to solve for the warp factor and scalar field if we parametrize the bulk potential as

$$V_{\rm bulk} = \frac{1}{2} \left(\frac{\partial W}{\partial \phi_1} \right)^2 - \frac{5}{2 M_6^4} W^2 \ , \tag{7}$$

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- with $W(\phi)$ satisfying the junction conditions

$$W\Big|_{\alpha-\epsilon}^{\alpha+\epsilon} = \frac{1}{2}\,\frac{1}{r_z}\,f_\alpha(\phi_1(\alpha)) \qquad\qquad \frac{\partial W}{\partial\phi_1}\Big|_{\alpha-\epsilon}^{\alpha+\epsilon} = -\,\frac{1}{2}\,\frac{\partial f_\alpha(\phi_1(\alpha))}{\partial\phi}.$$

An explicit example

- Choosing $W(\phi_1)$ to be of the form

$$W(\phi_1) = 2\,M_6^5\,\epsilon - \frac{1}{4}\,u\,M_6\,\phi_1^2\ ,$$

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- The stability of r_z could be addressed along with the boundary-localized potential that

$$r_z = \frac{1}{u\, \pi\, M_6} \, \ln \frac{v_\pi^2}{v_0^2} \ . \tag{9}$$

stabilizing x_4

- A second scalar ϕ_2 (of mass $m_2 \lesssim M_6$) confined to the 4-brane at $x_5 = \pi$ would lead to a stabilized R_y^{-1}, and, consequently, to a moderate R_y/r_z and a small c (as desired).

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- Case 2, though interesting, but will have similar results to Randall-Sundrum with Bessel function solutions in the x_5 direction.

Gravitons in Warped Scenario [8] spare

- To obtain the KK modes, one needs to consider the fluctuations of the metric,

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \Delta_{\mu\nu}$$

where $\bar{g}_{\mu\nu}$ denotes the background metric.

[8] M. T. Arun, D. Choudhury, A. Das and S. SenGupta, *Graviton modes in multiply warped geometry* Phys. Lett. B **746**, 266 (2015)

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$$\Delta_{\mu\kappa} = b^2(x_5)\, a^2(x_4)\, \frac{1}{\sqrt{R_y\, r_z}} \sum_{n,p} h^{(n,p)}_{\mu\nu}(x_\mu)\, \psi_{np}(x_4)\, \chi_p(x_5)\ .$$

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- The interaction term of a graviton with any brane field is given by

$$L_{\rm int} = C_{np}\, T^{\mu\nu}\, h^{n,p}_{\mu\nu}(x_\mu, x_4 = \pi, x_5 = 0) \ , \qquad (10)$$

where $T^{\mu\nu}$ is the energy-momentum tensor of the field.

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spare

- Small k (large c)

$k = 0.05,\ \frac{R_y}{r_z} = 211,\ w = 6.14 \times 10^{-15}$		
(n, p)	$m_{np}(\text{TeV})$	$C_{np} \times 10^3$ (TeV^{-1})
(1, 0)	5.07	8.04
(2, 0)	9.29	8.04
(3, 0)	13.5	8.04
(0, 1)	30.2	−24.1
(1, 1)	37.1	16.4
(2, 1)	42.7	−14.7

$k = 0.3,\ \frac{R_y}{r_z} = 49.3,\ w = 1.81 \times 10^{-14}$		
(n, p)	$m_{np}(\text{TeV})$	$C_{np} \times 10^3$ (TeV^{-1})
(1, 0)	7.07	1.87
(2, 0)	12.9	−1.87
(3, 0)	18.8	1.87
(0, 1)	11.3	−4.74
(1, 1)	17.8	4.13
(2, 1)	24.0	−3.99

Table: *Sample spectra for the small k case for a particular bulk curvature ($\epsilon = 0.0775$).*

Large k (small c)

$k = 8.2,\ \frac{R_y}{r_z} = 1.56,\ \epsilon = 0.00675$		
$w = 1.3 \times 10^{-11}$		
(n, p)	$m_{np}(\text{TeV})$	$C_{np}(\text{TeV}^{-1})$
(0, 1)	3.61	−0.881
(0, 2)	7.40	0.745
(0, 3)	10.8	−0.720
(0, 4)	14.2	0.710

$k = 8.5,\ \frac{R_y}{r_z} = 1.56,\ \epsilon = 0.0111$		
$w = 5.06 \times 10^{-12}$		
(n, p)	$m_{np}(\text{TeV})$	$C_{np}(\text{TeV}^{-1})$
(0, 1)	3.74	−3.62
(0, 2)	7.66	3.06
(0, 3)	11.2	−2.96
(0, 4)	14.7	2.92

Table: *Sample spectra for the large k case.*

Small k (large c)

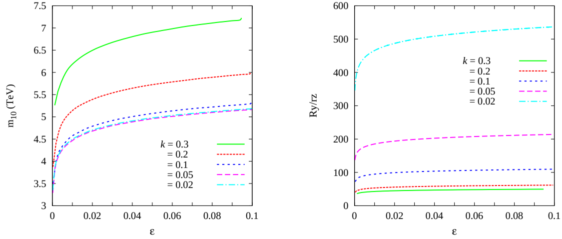

Figure: (left)The mass m_{10} for the first graviton mode as a function of ϵ for a fixed k. The parameter $\frac{R_y}{r_z}$ has been constrained to satisfy $w\, R_y^{-1} = m_h$. (right) Contour plots in the $(\epsilon, \frac{R_y}{r_z})$ plane for fixed values of k. The curves are constrained to satisfy $w\, R_y^{-1} = m_h$

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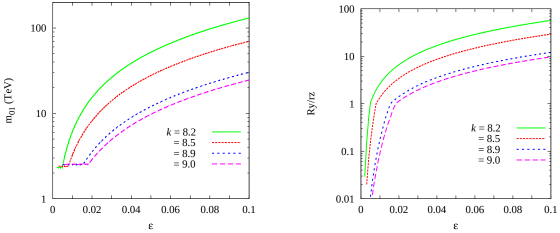

Figure: Left panel: Contour plots in the $(\epsilon, \frac{R_y}{r_z})$ plane for fixed values of k. Right panel: The mass m_{01} for the first graviton mode as a function of ϵ

- The Dirac Lagrangian in the warped geometry is, then, given by

$$\mathcal{L}_{\rm Dirac} = i\,\bar{\Psi}_+\,\Gamma^a\,E^M_a\,\left(\partial_M + w^{bc}_M[\Gamma_b,\Gamma_c]\right)\,\Psi_+\,, \tag{11}$$

where the sechsbeins e^a_M satisfy the conditions $e^a_M\,e^b_N\,g^{MN} = \eta_{ab}$, $E^a_M\,E^b_N\,\eta^{ab} = g_{MN}$, leading to

$$e^a_\mu = a(x_4)\,b(x_5)\,\delta^a_\mu\ , \quad e^a_4 = R_y\,b(x_5)\,\delta^a_4\ , \quad e^a_5 = r_z\,\delta^a_4\ .$$

[9] M. T. Arun and D. Choudhury, *Bulk gauge and matter fields in nested warping: I. the formalism*, JHEP **1509**, 202 (2015),arXiv:1501.06118 [hep-th]

Fermions in the bulk : Six-dimensions with nested warping spare

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- and the only nontrivial components of the spin connections are given by

$$\omega_{bc4} = \frac{R_y}{r_z}\,\dot{b}\,\delta^5_{[b}\,\delta^4_{c]}\ , \quad \omega_{bc\mu} = \eta_{\mu\nu}\,\left(\frac{a'}{R_y}\,\delta^\nu_{[b}\,\delta^4_{c]} + \frac{a\,\dot{b}}{r_z}\,\delta^\nu_{[b}\,\delta^5_{c]}\right)\ ,$$

where primes (dots) denote derivatives with respect to x_4 (x_5).

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Bulk Standard model fields[9]

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- The solutions are in terms of Bessel and Legendre functions

[9] M. T. Arun and D. Choudhury, *Bulk gauge and matter fields in nested warping: I. the formalism*, JHEP **1509**, 202 (2015),arXiv:1501.06118 [hep-th]

Gauge bosons in the bulk spare

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- The quadratic term for the vector field is now given by

$$\mathcal{L}_{A_\mu} = \frac{-R_y r_z}{2} \left[bA_\kappa(-\partial^2\eta^{\kappa\lambda} + \partial^\lambda\partial^\kappa)A_\lambda + \frac{a^2 b}{R_y^2}(\partial_4 A_\kappa)(\partial_4 A^\kappa) + \frac{a^2 b^3}{r_z^2}(\partial_5 A_\kappa)(\partial_5 A^\kappa) \right] , \tag{13}$$

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- while for the adjoint scalars, with field redefinitions $\tilde{A}_4 \equiv \sqrt{\frac{r_z}{R_y}}\, A_4$ and $\tilde{A}_5 \equiv \sqrt{\frac{R_y}{r_z}}\, A_5$, it is

$$\mathcal{L}_{\tilde{A}_4} = \frac{-1}{2}\left[a^2 b(\partial_\mu \tilde{A}_4)\,(\partial^\mu \tilde{A}_4) + \frac{a^4 b^3}{r_z^2}(\partial_5 \tilde{A}_4)^2 + \frac{1}{R_y^2 b}\left\{\partial_4(a^2 b\tilde{A}_4)\right\}^2\right] \ ,$$

$$\mathcal{L}_{\tilde{A}_5} = \frac{-1}{2}\left[a^2 b^3(\partial_\mu \tilde{A}_5)\,(\partial^\mu \tilde{A}_5) + \frac{a^4 b^3}{R_y^2}(\partial_4 \tilde{A}_5)^2 + \frac{1}{r_z^2 b}\left\{\partial_5(a^2 b^3\tilde{A}_5)\right\}^2\right] \ ,$$

and reminiscent of the action for a scalar field, after neglecting a small mixing term.

Interaction : Gauge-Fermion spare

- Writing the interaction term in its component form, we have

$$\mathcal{L} \ni \sum_{\{n_i,p_i\}} g^{V,f}_{\{n_i,p_i\}} \bar{\psi}^{n_1,p_1}_{l/r} \gamma^\mu \psi^{n_2,p_2}_{l/r} A^{n_3,p_3}_\mu \ , \tag{14}$$

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- with the four dimensional charges being given by

$$g^{V,f}_{\{n_i,p_i\}} = \frac{g_{\rm YM}}{\sqrt{R_y r_z}} \int_0^{\pi} dx_4 \int_{-\pi}^{\pi} dx_5 \; a^3 b^4 \mathcal{F}^{n_1,p_1}_{l/r}(x_4,x_5)\, \mathcal{F}^{n_2,p_2}_{l/r}(x_4,x_5)\, \eta_{n_3,p_3}(x_4)\, \chi_{p_3}(x_5) \ .$$

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- Some examples of gauge boson spectra and their couplings to the lowest modes of the fermion current are given in tables below. With the scaling C_{np} of zero mode gauge boson coupling with the fermions defined as

$$C_{np} \equiv \frac{g^{V,f}_{\{0,0,n\},\{0,0,p\}}}{g^{V,f}_{\{0,0,0\},\{0,0,0\}}} \,.$$

$k = 0.3,\ \frac{R_y}{r_z} = 49,\ w = 1.82 \times 10^{-14}$

(n,p)	$m_{np}(\mathrm{TeV})$	C_{np}
$(1,0)$	4.47	3.87×10^{0}
$(2,0)$	10.2	4.98×10^{-1}
$(0,1)$	10.1	7.89×10^{-1}
$(1,1)$	17.0	3.03×10^{-1}

$k = 0.56,\ \frac{R_y}{r_z} = 50.4,\ w = 4.48 \times 10^{-14}$

(n,p)	$m_{np}(\mathrm{TeV})$	C_{np}
$(1,0)$	8.55	3.77×10^{0}
$(2,0)$	19.6	4.93×10^{-1}
$(0,1)$	14.6	2.35×10^{0}
$(1,1)$	26.9	7.19×10^{-1}

Table: *Sample spectra for the small k case for a particular bulk curvature ($\epsilon = 0.0775$) with R_y set to satisfy the mass hierarchy.*

Symmetry breaking and Phenomenological consequences [10]
Higgs spare

- To solve the hierarchy problem, in large c(small k) regime, we need to confine the Higgs to a brane located at ($x_4 = \pi$). We chose the Higgs Lagrangian of the form

$$\mathcal{L}_h = \delta(x_4 - \pi)\sqrt{-g_5}\left(g^{\mu\nu} D_\mu \phi(x^{\bar{M}})^\dagger D_\nu \phi(x^{\bar{M}}) + \left(\frac{R_y}{r_z}\right)^{-2} g^{55} |D_5 \phi(x^{\bar{M}})|^2 + V(\phi)\right) ,$$

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$$V(\phi) = \frac{k^2}{R_y^2}\left[\frac{5\,\mathrm{sech}^2 k\pi}{24\,(v/\sqrt{r_z})^4}\,\phi^6 - \frac{7}{8}\,\phi^2\right].$$

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- Identifying the lowest state with the recently discovered Higgs boson, we get

$$m_h^2 = m_0^2 = \left(\frac{25}{4}\mathrm{sech}^2 k\pi + \gamma_0\right)\frac{k^2}{R_y^2}\, e^{-2c\pi} \ .$$

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- Parameterizing the vev v as $v = \frac{\lambda_v}{\sqrt{2\pi}} \, R_y^{-1} = \frac{\lambda_v}{\sqrt{2\pi}} \left(\frac{R_y}{r_z}\right)^{-1} r_z^{-1}$, where $\lambda_v \lesssim 1$, we have

$$\lambda_v = \sqrt{2\pi \left(\frac{25}{4} \mathrm{sech}^2 k\pi + \gamma_0\right)} \, \frac{k}{g} \, \frac{M_w}{m_h} \, .$$

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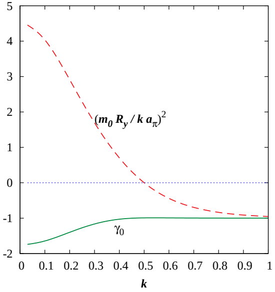
- The dependence of the zero mode Higgs mass on k starting from is shown in the figure below



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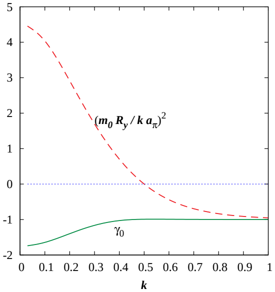

- As the figure clearly shows, the Higgs potential formulation we followed, allows for only $k \lesssim 0.5$

Corrections to the Higgs potential and modifications to the spectrum

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$$\phi_{\rm cl}^{\rm new} = \frac{v}{\sqrt{r_z\, b(x_5)}}\, [1 + \beta_n b^n(x_5)]$$

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- It is easy to see that the tree level potential gets modified and for $n = -3$ (for simplicity)

$$\delta V = \frac{-4\, k^2}{3\, R_y^2}\, \frac{v}{2 r_z^2}\, \beta\, {\rm sech}^2(k\pi)\, \left(\frac{r_z\, \phi^2}{v^2}\right)^6$$

  where $\beta \equiv \beta_{-3} \leq 0$ so as to ensure a potential bounded

Corrections to the Higgs potential and modifications to the spectrum

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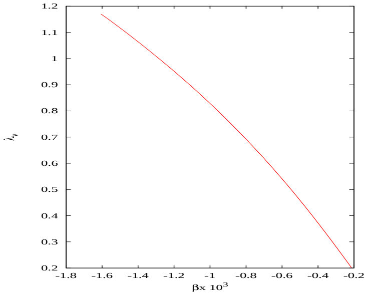
- Clearly for $\lambda_v < 1$, a negative β raises the Higgs mass considerably, thereby allowing for a wider range of k without risking tachyonic modes.

- In the new description the figure below shows that a rather wide range of λ_v becomes allowed once even small perturbations are switched on for $k = 0.6$ and $50 < \frac{R_y}{r_z} < 53$.



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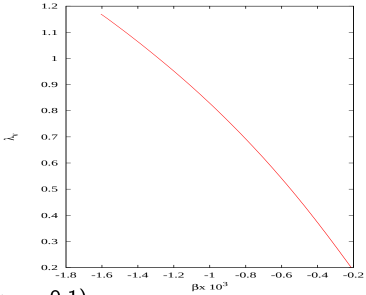

- A sample spectrum (for $\epsilon = 0.1$)

$k = 0.3,\ \frac{R_y}{r_z} = 49.0,\ w = 2.69 \times 10^{-14}$

(p)	γ_p	$m_p(\text{TeV})$	
(0)	-1.16419	0.121	$\lambda_v = 1.99, \beta = 0$
(1)	4.932	0.260	
(2)	24.742	0.489	

$k = 0.4,\ \frac{R_y}{r_z} = 46.5,\ w = 4.33 \times 10^{-14}$

(p)	γ_p	$m_p(\text{TeV})$	
(0)	-1.029	0.120	$\lambda_v = 1.71, \beta = 0$
(1)	1.59	0.262	
(2)	9.536	0.484	

$k = 0.5,\ \frac{R_y}{r_z} = 46,\ w = 3.2 \times 10^{-13}$

(p)	γ_p	$m_p(\text{TeV})$	
(0)	-0.9914	0.118	$\lambda_v = 0.323, \beta = -7 \times 10^{-6}$
(1)	0.556	1.19	
(2)	3.997	2.13	

- Localized Higgs deforms not only the mass spectrum, but also the wavefunctions. It affects the lowest (zero-) mode as follows

$$\eta_{0,0}^{V} \to \eta_{0,0}^{Vr} \approx \frac{1}{\sqrt{\pi}} \left[1 + \frac{M_V^2\, \rho^2}{4} \left(e^{2c(x_4-\pi)} - 1 - 2cx_4 e^{2c(x_4-\pi)} + 2c\pi\right)\right] .$$

where $\rho = \frac{R_y}{c}\, e^{c\pi}$. Where V will be replaced by W or Z depending whether its $W^{\pm}$ boson or Z boson.

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- This effect for the massive gauge bosons is suppressed by a factor $v^2/M_{(1,0)}^2$.
- The relevant part of the renormalized Lagrangian can be written as

$$\begin{aligned} -\mathcal{L}_{eff} &= \frac{\mathcal{Z}_\gamma}{4} F_{\mu\nu}F^{\mu\nu} + \frac{\mathcal{Z}_W}{2} W^+_{\mu\nu} W^{-\mu\nu} + \frac{\mathcal{Z}_Z}{4} Z_{\mu\nu} Z^{\mu\nu} \\ &+ \left[M_w^2 + \Pi_{ww}(0)\right] W_\mu W^\mu + \frac{1}{2}\left[M_z^2 + \Pi_{zz}(0)\right] Z_\mu Z^\mu \\ &\equiv \frac{1+A}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1+B}{2} W^+_{\mu\nu}W^{-\mu\nu} + \frac{1+C}{4} Z_{\mu\nu}Z^{\mu\nu} + \frac{G}{2} F_{\mu\nu}Z^{\mu\nu} \\ &+ (1+w)M_W^2 W_\mu W^\mu + \frac{1+z}{2} M_z^2 Z_\mu Z^\mu \ , \end{aligned} \tag{15}$$

where we have deliberately introduced the parameters A, B, C, G, w, z for future ease.

The Oblique Parameters spare

- This immediately leads to expressions for the oblique parameters[11]

$$\delta S \approx -4\pi \frac{M_w^2 \rho^2 c\pi}{g^2} = -4\pi\zeta \ , \quad \delta T \approx \frac{-\pi}{2\cos^2\theta_w} \frac{M_w^2 \rho^2 c\pi}{g^2} = \frac{-\pi}{2\cos^2\theta_w}\zeta \ , \quad \delta U = 0 \ .$$

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- Experiments demand $V < 0.0013$ at 95% C.L.

$k = 0.5,\ \alpha = 48.367,\ w = 7.081 \times 10^{-14}$

(n,p)	$m_{np}(\,\mathrm{TeV})$	C_{np}	V
$(1,0)$	9.5	3.81	1.0×10^{-3}
$(2,0)$	21.9	0.49	3.34×10^{-6}
$(0,1)$	17.0	0.20	9.21×10^{-7}
$(1,1)$	30.9	0.06	2.84×10^{-8}

Table: *Sample spectrum for the small k case for a particular bulk curvature ($\epsilon = 0.1$) and with $\lambda_v = 1.5$. C_{np} is defined as the ratio of $g^{(n,p)}$ and g.*

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Confronting Electroweak Precision Measurements

- We now construct a $\Delta\chi^2$-test (the shift in the χ^2 from the SM value of ≈ 27.5) for this model[12] comparing the expressions with the experimental results.

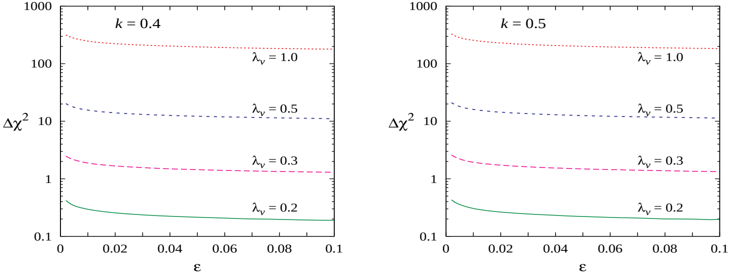

Figure: *The shift in the χ^2 as a function of ϵ for various values of the parameter λ_v. The panel refers to $k = 0.4$.*

Note that even a very moderate hierarchy ($\lambda_v \lesssim 0.3$) renders the model quite consistent with low-energy data.

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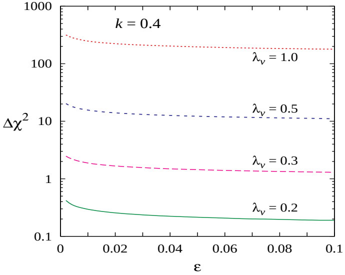

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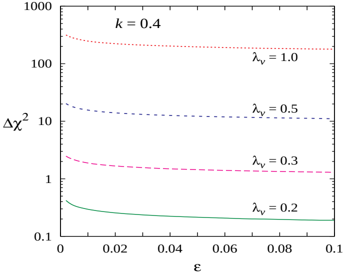

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- But this will not bring in a little hierarchy unlike the 5D RS.

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Beta function

- The renormalization group evolution of the gauge couplings (which is logarithmic in the case of the SM) now turns power-law as shown below. This can be understood most easily in terms of the KK-reduction, whereby the logarithmic contributions from each of the individual KK-excitations sum up to give a power-law behaviour

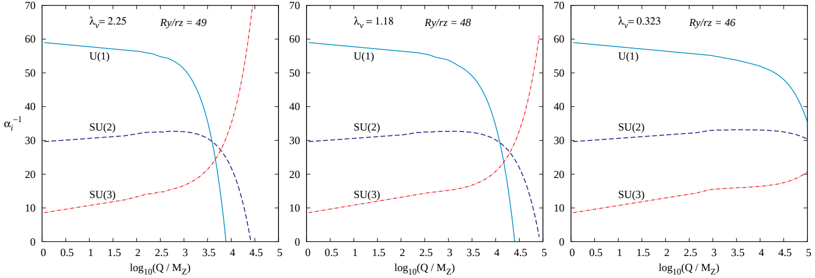

Figure: *Gauge coupling constant evolution for* $k = 0.5$, $\epsilon = 0.1$. *The three panels correspond to different* λ_v *values.*

Thank You