

Warped Universal Extra Dimensions

... work in progress...

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" /0509160

Question: is it "possible" to put all SM fields in the bulk of the Randall-Sundrum model?

1999 - 2005: No! (Higgs is on the TeV-brane)

Now: Yes! ...

(... "possible" = a phenomenologically viable model, not fine-tuned!)

- What is the model??
- How to get around previous problems
- * • Collider signatures { modified $WWH/Z\bar{Z}H$,
KK's for Higgs,
alterate radion-Higgs mixing, ...

How?

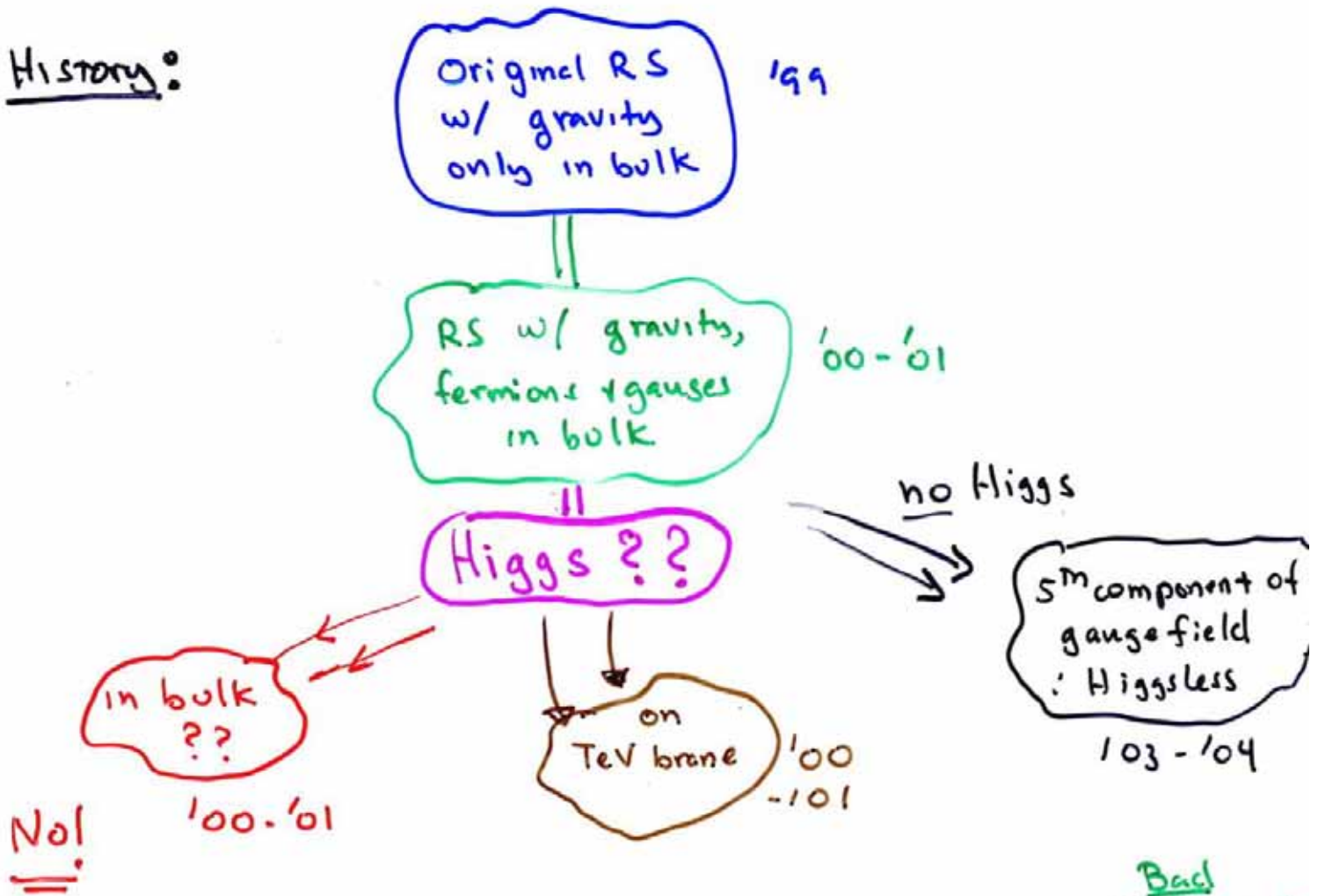
⇒ gravity-induced EW symmetry breaking!!

- Putting SM particles in the SD bulk provides a remarkable landscape for model building...

e.g., UED in flat SD...

- What about the warped case? (RS)

History:



- requires Fine-tuning $\approx 1/10^{16}$ to get $W, Z \sim 100$ GeV : "philosophy"
- $M_W = M_Z \cos \theta_W$ violated at 0(1) level! : phenomenology

- Higgs (w/ a flat wavefunction) in bulk doesn't work...
... this is the critical observation

Simple Model

$$\mathcal{L} = (\partial^A \phi)^\dagger (\partial_A \phi) - m^2 \phi^\dagger \phi - \lambda_S (\phi^\dagger \phi)^2$$

↑ bulk mass term ↑ usual quartic

$$+ \frac{1}{k} [\mu_P^2 \delta(y) - \mu_H^2 \delta(y - \pi r_c)] \phi^\dagger \phi$$

↑ mass terms on Planck + TeV branes

Recall in RS : $ds^2 = e^{-2ky} \underbrace{\eta_{\mu\nu} dx^\mu dx^\nu}_{\text{Minkowski}} - \underbrace{dy^2}_{\text{warp factor}}$, $k \sim M$
~ bulk curvature

⇒ k sets the mass scale for particles SO

Set: $m^2 = 20k^2 \xi$, $\mu_{P,H}^2 = 16k^2 \xi \beta_{P,H}$

$\xi, \beta_{P,H}$ are $O(1)$ parameters of arbitrary sign

Need : (to generate the usual SM setup) = KK decompose

- a single, TeV scale tachyon s.t. when we shift the field as usual we get $v, m_H \sim 100 \text{ GeV}$

AND w/o fine-tuning ⊕ The ADDITIONAL Higgs KK tower will be non-tachyonic

⇒ The vev will be y-dependent having a profile given by the tachyonic wave function
⇒ NOT flat

Computational Details

- Find mass spectrum + wavefunctions for Higgs:

$$\partial_y (e^{-4ky} \partial_y \chi_n) - m^2 e^{-4ky} \chi_n + m_n^2 e^{-2ky} \chi_n + \frac{e^{-4ky}}{k} [\mu_p^2 \delta(y) \mu_H^2 \delta(y - \pi r_c)] \chi_n \stackrel{=0}{}$$

$$\Rightarrow \chi_n = \frac{e^{2ky}}{N_n} J_\nu(x_n e^{k(y - \pi r_c)}) \quad \begin{cases} x_n = \text{'roots'} \\ m_n = x_n \frac{k}{\mu_H} \approx 300 \text{ GeV} \end{cases}$$

$$\bullet \left\{ 2(1 + 4\beta_H \xi) - (4 + 20\xi)^{1/2} \right\} J_\nu(x_n) + x_n J_{\nu+1}(x_n) = 0 \quad (\nu^2 = 4 + 20\xi)$$

\Rightarrow roots!

- want $x_i = i x_T, x_n > 1$ real
 \uparrow
 tachyon w/ $x_T = \frac{e^{2ky}}{N_T} J_\nu(i x_T e^{k(y - \pi r_c)})$

so that $V(y) = V x_T(y)$

- To find 'small' roots, look where root = 0

$$\xi \geq \xi_{1,2} \text{ (I)}$$

on one side of these boundary
 x_i is real (imaginary)...

$$\xi \leq \xi_{1,2} \text{ (II)}$$

$$\xi_1 = -\frac{1}{4\beta_H}$$

$$\xi_2 = \frac{5 - 8\beta_H}{16\beta_H^2}$$

⇒ Scan parameter space for solutions ...
 [find β_p plays no rôle]

• We obtain 2 allowed regions in the ξ - β_H plane

$$V(y) = v \cdot \frac{e^{2ky}}{N} \cdot J_\nu \left(i x_T e^{k(y-\pi r)} \right)$$

$(\nu)^2 = 4 + 20\xi$

$$\sim v \cdot \exp \left[(2 + \sqrt{4 + 20\xi}) ky \right]$$

$x_T \sim O(1)$
 = Tachyon 'root'
 correlated to m_H

is peaked near the TeV brane ... but detailed
 shape is ξ -dependent [Figs]

W/Z masses

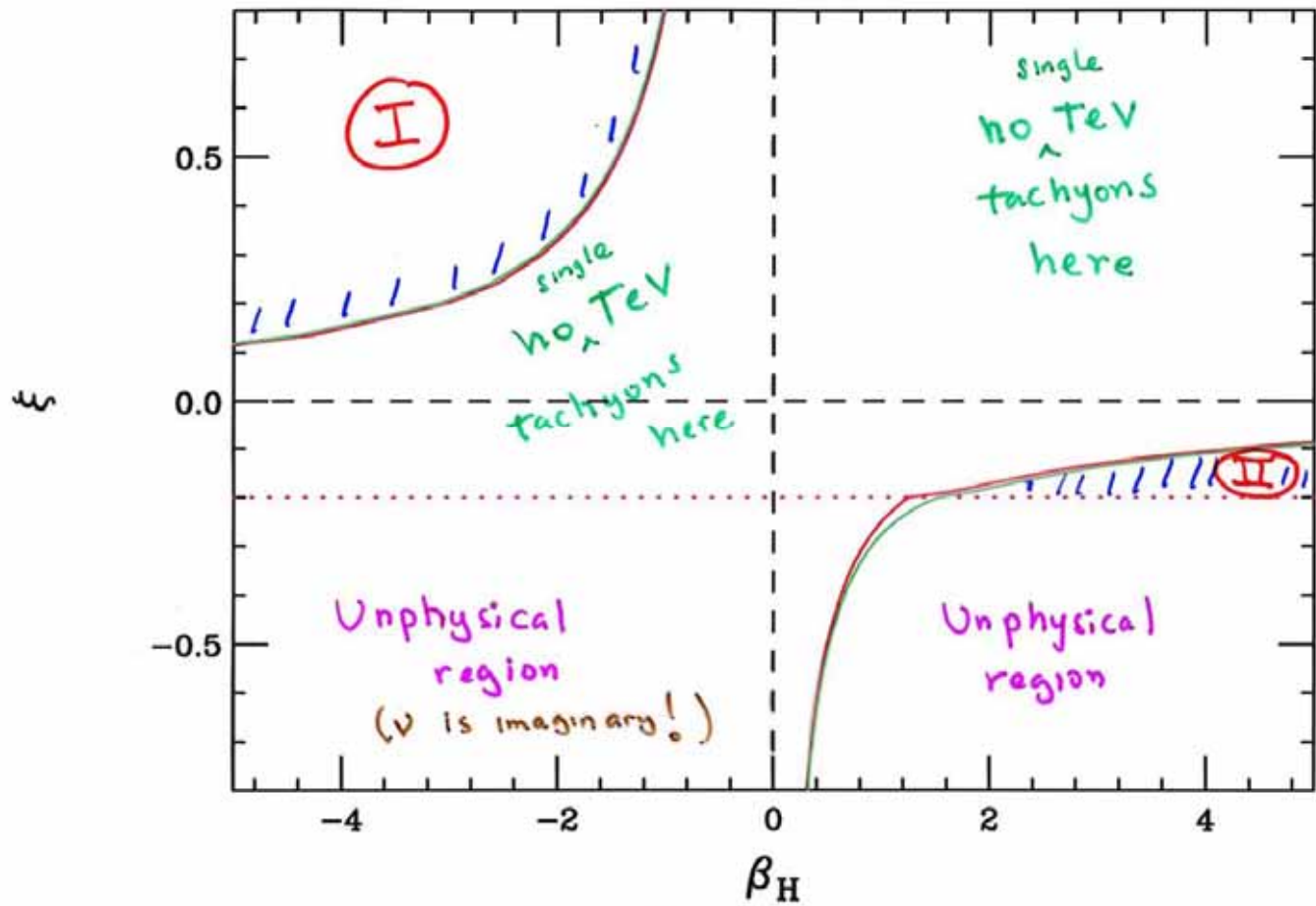
.. for the W $\partial_y (e^{-2ky} \partial_y f_n^W) - \frac{1}{4} g_5^2 v^2(y) e^{-2ky} f_n^W + m_n^2 f_n^W = 0$

+ similarly for the Z w/ $g_5^2 \rightarrow g_5^2/4c_w^2$, $f_n^W \rightarrow f_n^Z$

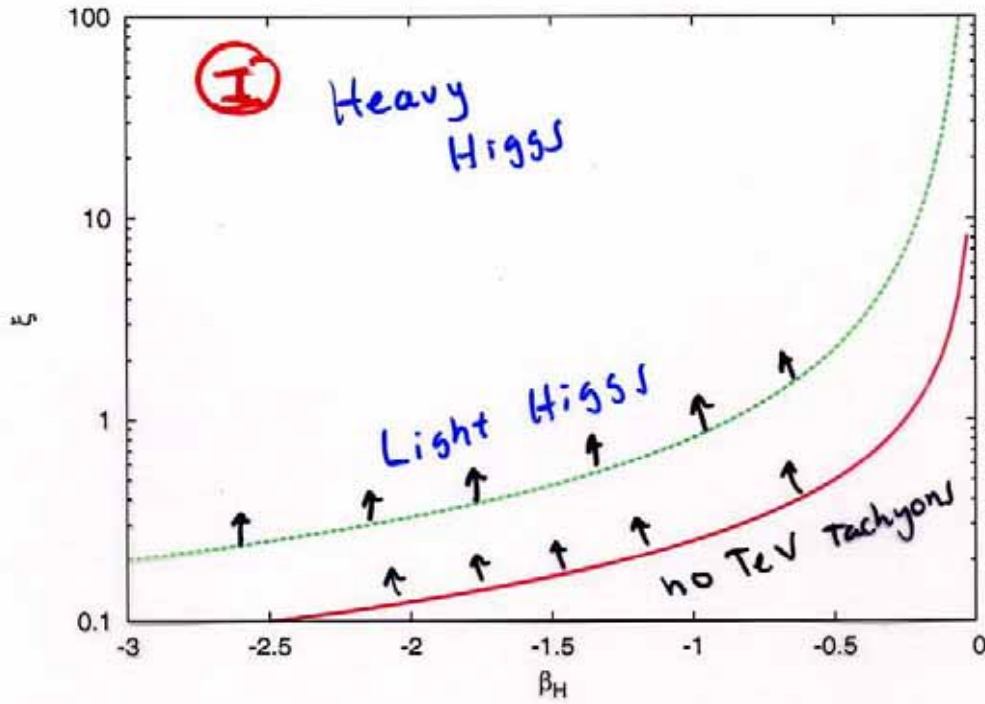
• We cannot solve this equation analytically +
 numerical sol'ns are difficult ... we obtained approx.
 results.. $\sim 10\%$

⇒ $M_W = M_Z \cos \theta_W$ OK at $\sim 5-10\%$ but we need
 better approx methods [+ go to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
 in bulk to get a custodial $SU(2)$ to get $\Delta \rho \sim 10^{-3}$]

$\xi - \beta_H$ parameter space scan



regions I + II 'work'



Regions
 I +
 II
Constraints

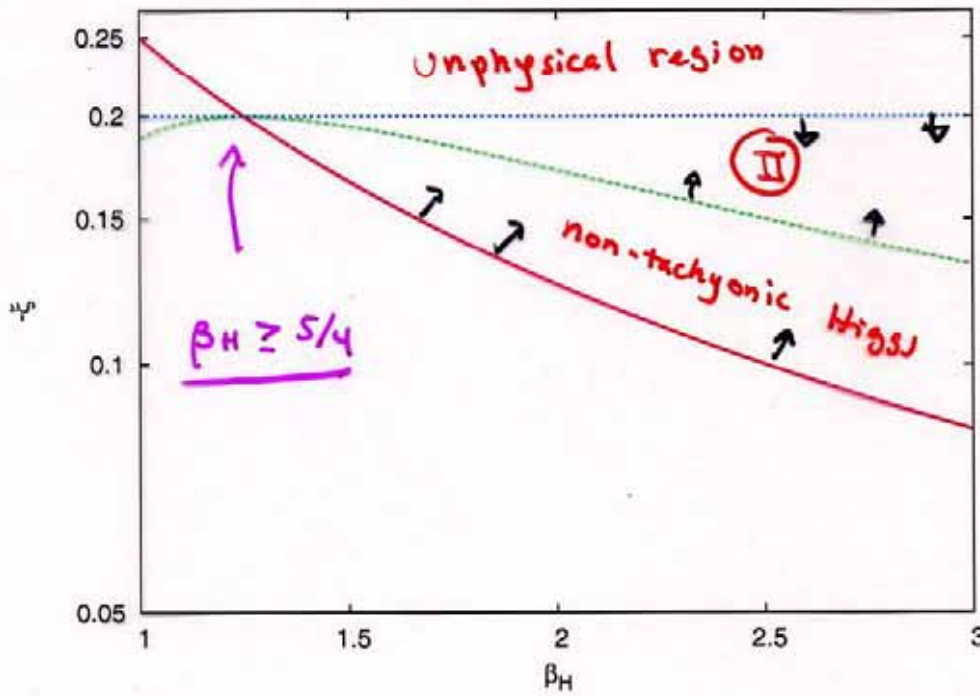


FIG. 1: Allowed regions in the $\xi - \beta_H$ plane for bulk Higgs induced EWSB in region I (top) and region II (bottom). The lower bound $\xi \geq -0.2$ (dotted blue) that insures $\nu^2 \geq 0$ in region II is also shown in addition to both constraints ξ_1 (dashed green) and ξ_2 (in solid red). The allowed region lies between the blue and green curves in region II and above the green curve in region I.

"light" Higgs constraint

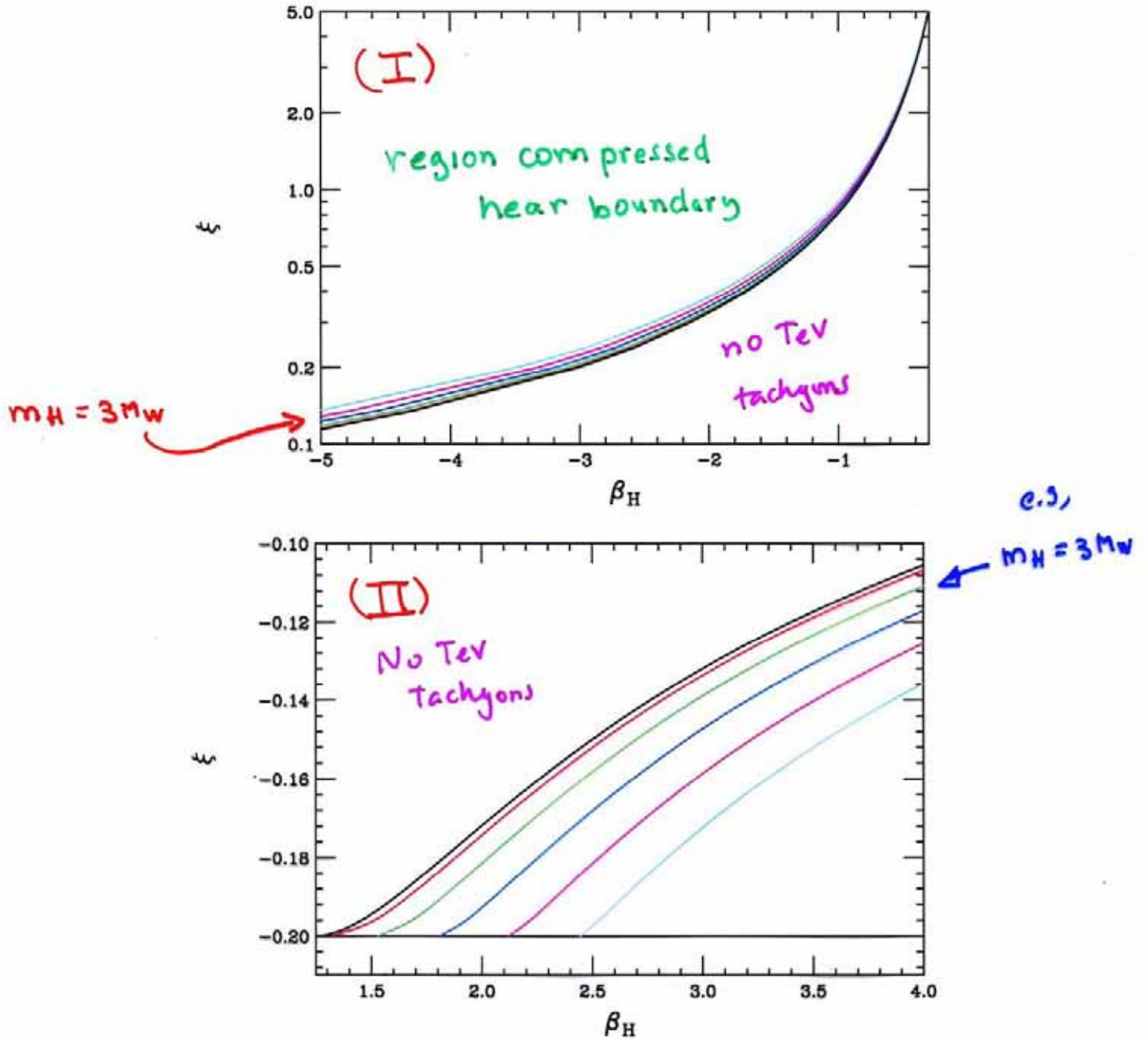


FIG. 3: The curves correspond to fixed tachyon root values, $x_T = 0$ (black) to 2.5 (cyan), in steps of 0.5, as functions of ξ and β_H in regions I (top) and II (bottom).

IV. GRAVITY-INDUCED ELECTROWEAK SYMMETRY BREAKING

As an example of EWSB with a bulk Higgs we now turn to the special case where EWSB is triggered by gravity.

Tachyonic roots

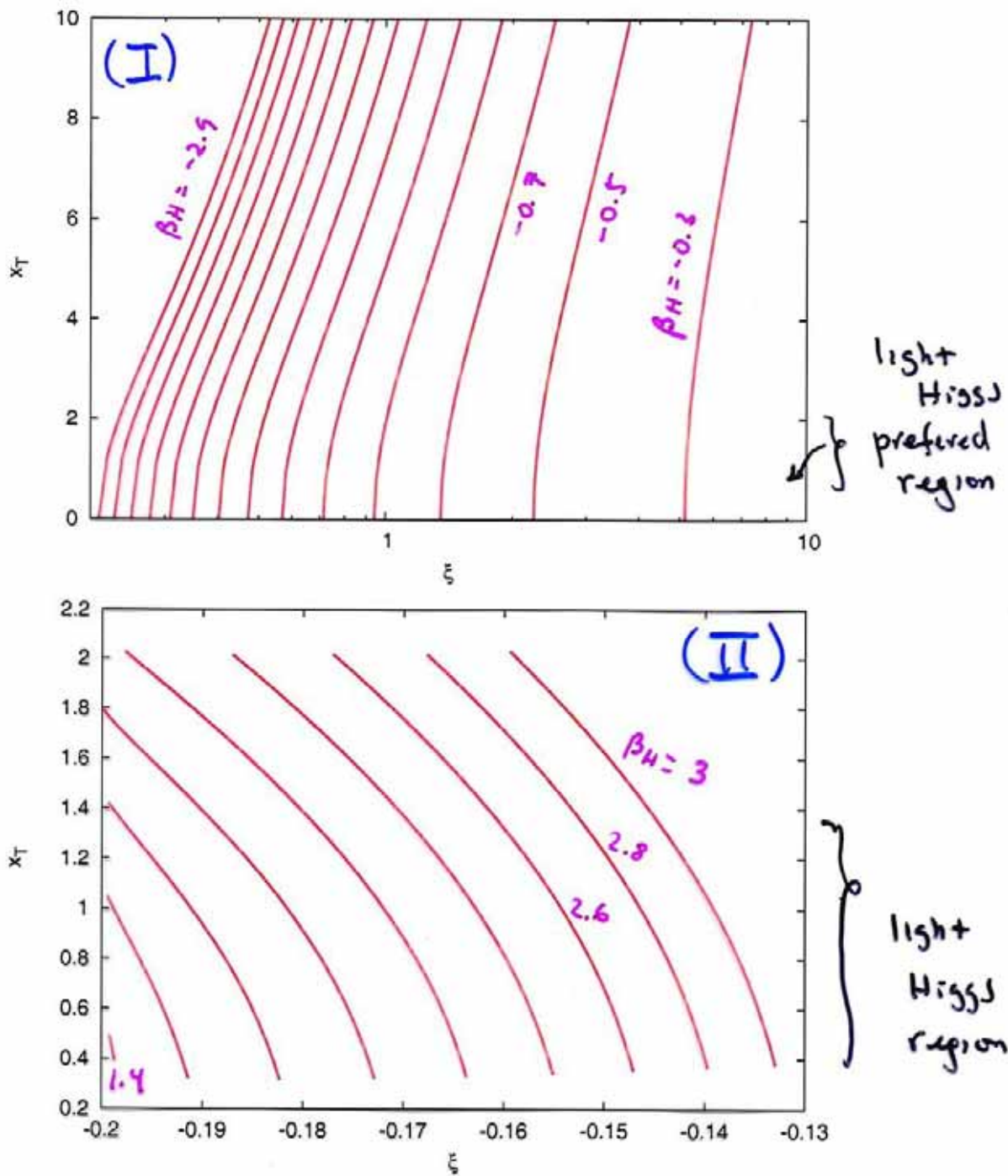


FIG. 2: Tachyon roots as a function of ξ for different β_H . In region I (top), with β_H ranging from -0.3 to -2.9 , going from right to left in steps of 0.2 and with β_H values from 1.4 to 3.0 , going left to right, in steps of 0.2 for region II (bottom).

Signatures:

... 2 'sources' of gauge masses...

$$M_W^2 = \frac{1}{4} g_5^2 \int dy e^{-2ky} v^2(y) f_W^2 + \int dy e^{-2ky} (\partial_y f_W)^2$$

"pure" Higgs
Contribution

Included wave-function
Curvature

related to WWH
Coupling \leftrightarrow obviously reduced!

$$\Rightarrow \boxed{\frac{g_{WWH}}{s_m} \approx \frac{1}{2} - \frac{2}{3}} \Leftarrow$$

Higgs has (heavy) KK excitations

(Unlike in UED, in WUED there is no symmetry)
present to prevent single KK production

\Rightarrow with a mass comparable to the ^{1st} graviton KK

.. but rather small coupling [LHC problem]

Higgs-radion sector completely different... as Higgs
is now a bulk field w/ a vev that has a profile.

etc etc etc

g_{WWH}/g_{SM} for light Higgs

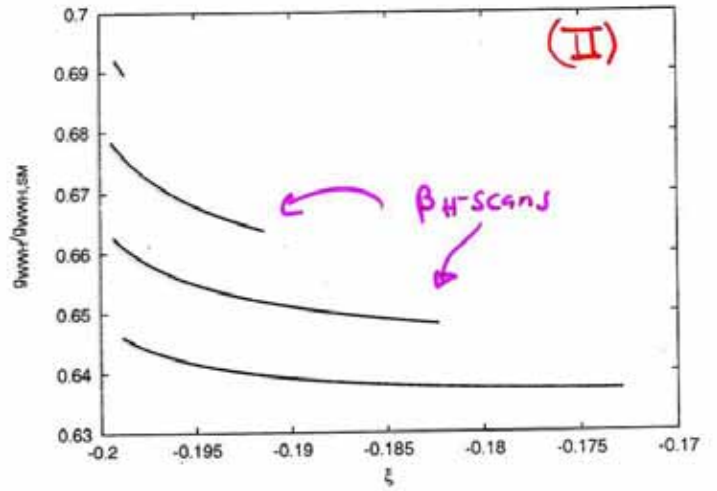
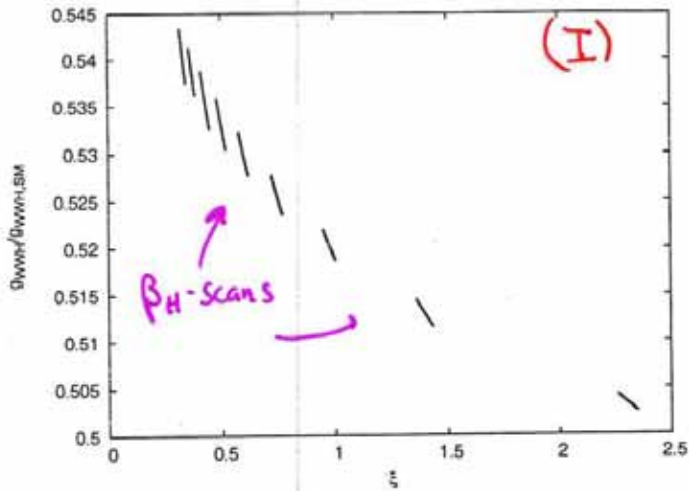
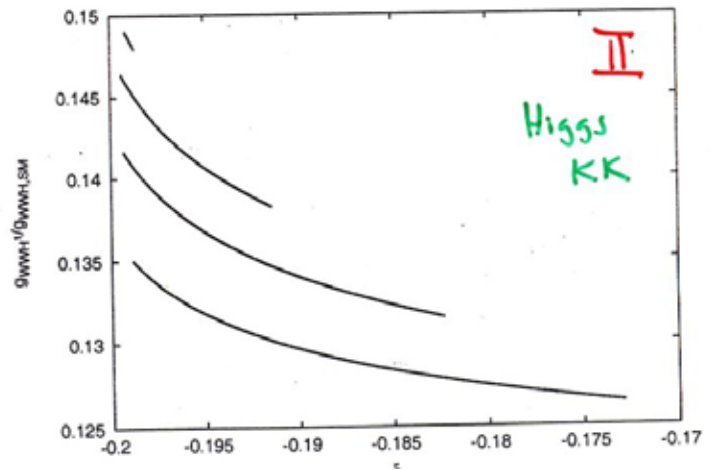
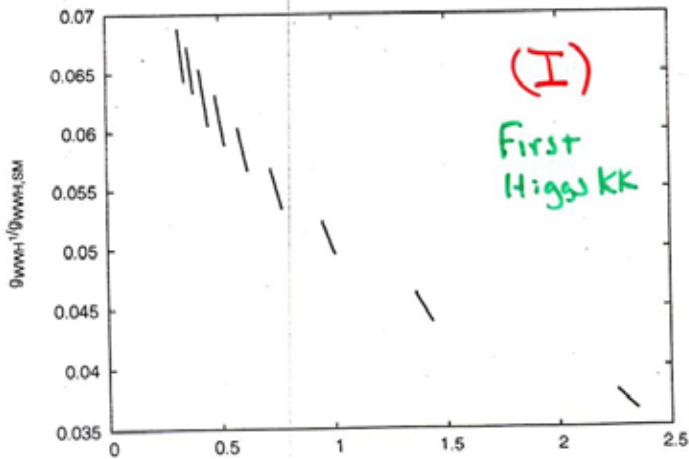


Figure 1: Values of the coupling ratio g_{WWH}/g_{SM} in regions I (left) and II (right) as functions of ξ for various β_H . In region I, from top from top to bottom, the curves correspond to $\beta_H = 1.4, 1.6, 1.8, 2.0$. A cut on the Higgs boson mass as described in the text has been imposed.



Higgs KK mass

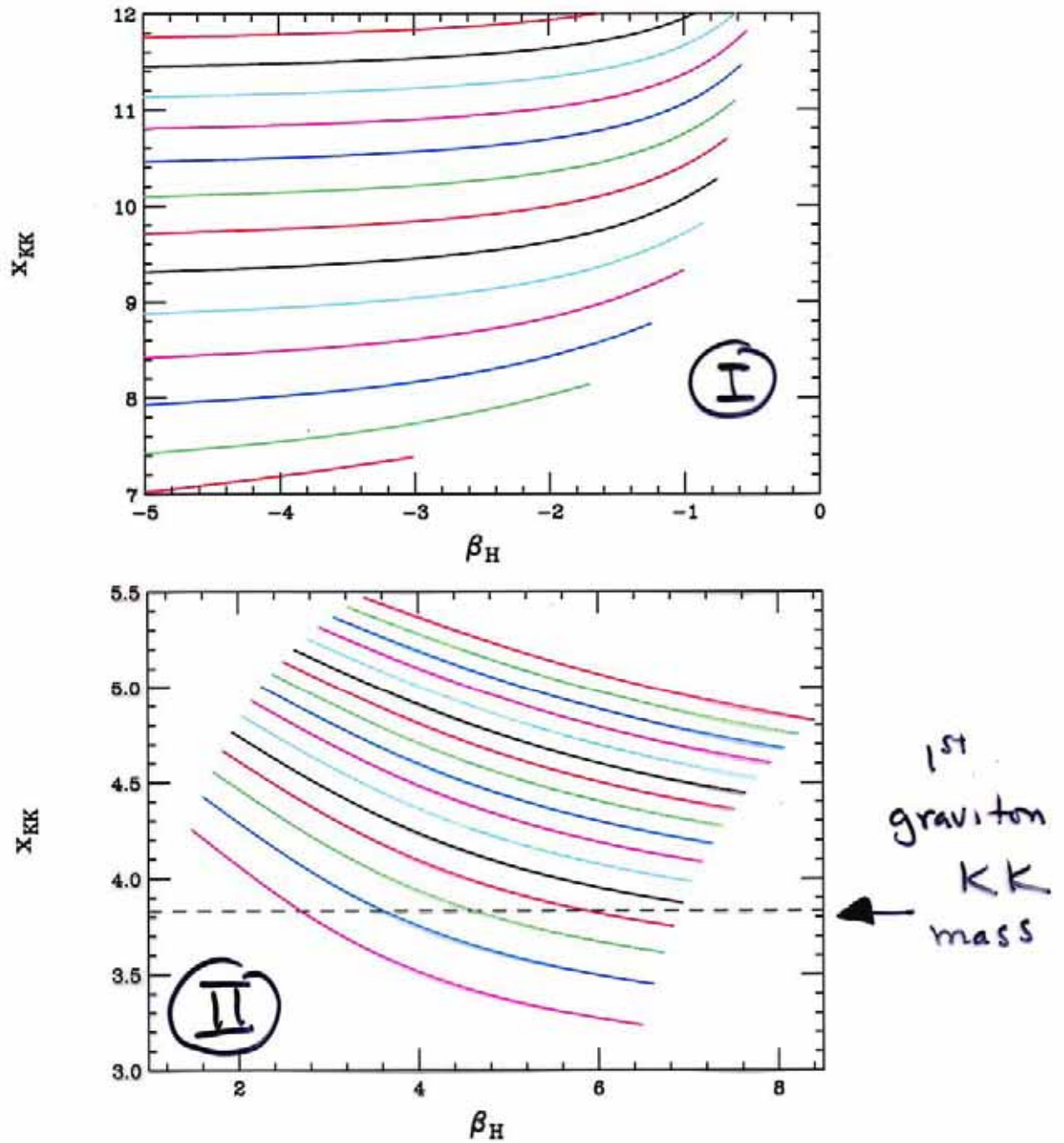


FIG. 4: Roots for the first Higgs KK excitation as a function of β_H for different values of ξ in regions I (top) and II (bottom). In region I, $\xi = 0.2$ is the lowest curve with ξ increasing by 0.2 for each subsequent curve. The curves are cut off on the right hand side by the ξ constraints. In region II, from top to bottom ξ runs from -0.120 to -0.195 in steps of 0.005. The largest possible value for the first graviton KK root consistent with the constraint $\Omega_\pi \leq 0$ found in the case of gravity induced breaking is shown as the dashed line.

Gravity - induced EWSB : ^{toy} model origin

... a massless scalar coupled to the most general RS gravity sector

$$S = S_{\text{grav}} + S_{\text{Higgs}} + S_{\text{gauge}}$$

string expansion

$$S_{\text{grav}} = \int d^5 x \sqrt{-g} \left\{ \underbrace{\frac{M^3}{2} R - \Lambda_b}_{\text{Usual RS}} + \underbrace{\frac{\alpha M}{2} (R^2 - 4R_{AB}R^{AB} + R_{ABCD}R^{ABCD})}_{\text{Gauss-Bonnet term}} \right. \\ \left. + \sum_i \left(\frac{M^3}{k} \gamma_i R_4 - \lambda_i \right) \delta(y-y_i) \right\}$$

↑
brane kinetic terms

$$S_{\text{Higgs}} = \int d^5 x \sqrt{-g} \left\{ (D^A \phi)^\dagger (D_A \phi) - \lambda_5 (\phi^\dagger \phi)^2 + \underbrace{\xi R \phi^\dagger \phi}_{\text{"radion" term}} \right\}$$

↑
Ricci scalar

- Because RS space is warped + not flat $\langle R \rangle = -20k^2 + \delta's \neq 0!$

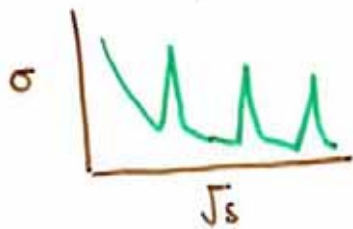
$$\begin{aligned} \rightarrow m^2 &= 20k^2 \xi \quad [\text{radion mixing parameter!}] \\ \rightarrow \beta_H &= 1 - \frac{4}{3} \alpha \frac{k^2}{M^2} \quad \text{GB parameter } (< 0) \end{aligned} \left. \vphantom{\begin{aligned} \rightarrow m^2 \\ \rightarrow \beta_H \end{aligned}} \right\} \text{"derived" from gravity}$$

... naturally leads to region II w/ $\xi < 0 + \beta_H > 0$
($|\alpha| \neq 0 !!$)

→ Strong link between gravity + EWSB sectors:

- measurements of graviton resonance properties (almost) uniquely fixes the Higgs/radion sector!
- both sectors together OVERCONSTRAIN the model...

• Observe graviton KK resonances



- obtain mass, widths, BP's, $G \rightarrow GG_i, \dots$
- telbus: $\alpha, \gamma_{0,\pi}, \Lambda_{\pi}, k\epsilon, k/M, \beta_H, \dots$

Compare parameter determinations from both sectors...

• Observe Higgs + radion

↳ $m_{r0}, \beta_H, \mathcal{J}, \dots$

• Other observations only: e.g., $\left\{ \begin{array}{l} \text{gauge KK's} \dots \\ \text{fermion KK's} \dots \end{array} \right.$

Conclusions

- It IS possible to put Higgs in the RS with the vev having a profile, i.e., $v = v(y)$, peaked at the TeV brane
- The parameters of this model can be Entirely generated by the GRAVITY sector of RS...
- Though we have just begun these studies, there are a number of obvious pheno implications for colliders..
 - reduced WWH/ZZH couplings ($\frac{1}{2} - \frac{2}{3}$ of SM)
 - Higgs KK excitations $m_{KK}^H \approx m_{grav}$
 - completely modified Higgs-radiation sector
 - model parameters overdetermined by observations

- Extend Gauge group [S,T]
- Refine W, Z mass estimates
- Look for more distinct signatures
- Influence on $Z \rightarrow \bar{b}b$ vertex
- ⋮

} plenty left to do...

∴ work now in progress..