Warped Universal Extra Dimensions

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... work in progress...

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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/ZZH, KK's for Higgs, alterate radion - Higgs mixing, ...

How?

⟹ gravity-induced EW symmetry breaking !!

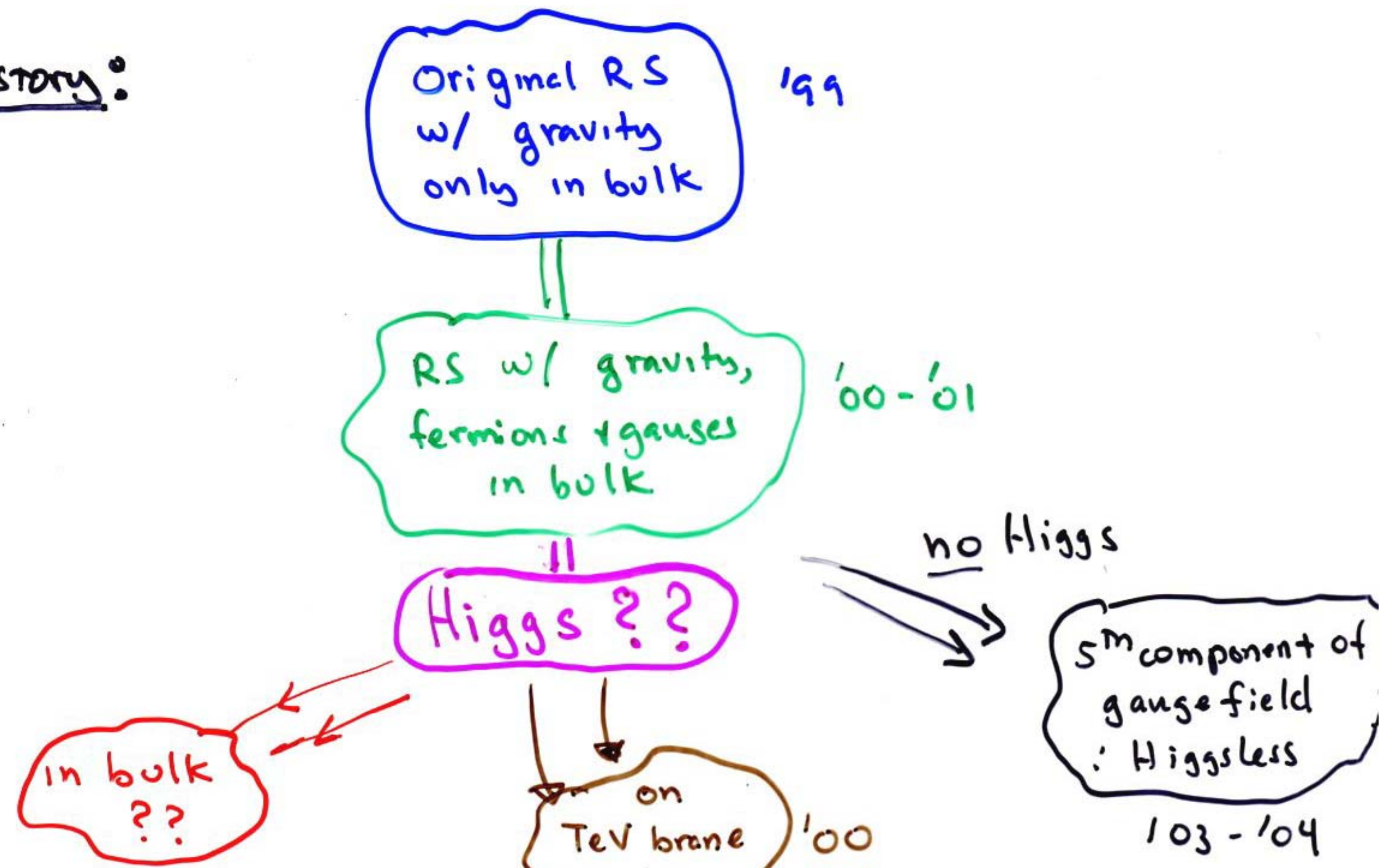
Vienna 11/05

· Putting SM particles in the 5D bulk provides a remarkable landscape for model building...

e.g, UED in flat 5D...

∴ What about the warped case ? (RS)

History:



No!

· requires Fine-tuning @ $1/10^{16}$ to get W, Z ~100 GeV : Bad "philosophy" : phenomenology

· $M_W = M_Z \cos\theta_W$ violated at O(1) level !

⋮

· Higgs (w/ a flat wavefunction) in bulk doesn't work...

... this is the critical observation

Simple Model

bulk mass term

usual quartic

$$\mathcal{L} = (\partial^A \phi)^\dagger (\partial_A \phi) - m^2 \phi^\dagger \phi - \lambda_5 (\phi^\dagger \phi)^2$$

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

mass terms on Planck + TeV branes

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

$\Rightarrow$ k sets the mass scale for particles so

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

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

Need : (to generate the usual SM set-up) = KK decompose

- a single, TeV scale tachyon S.T. when we Shift the field as usual we get $v, m_H \sim 100$ GeV

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

$\Rightarrow$ The vev will be $\boxed{\text{y-dependent}}$ having a $\boxed{\text{profile}}$ given by the tachyonic wave function

$\Rightarrow$ NOT flat

Calculational Details

- Find mass spectrum + wavefunctions for Higgs:

$$\partial_y\left(e^{-4ky}\partial_y \chi_n\right) - m^2 e^{-4ky}\chi_n + m_n^2 e^{-2ky}\chi_n + \frac{e^{-4ky}}{k}\left[\mu_P^2\,\delta(y) - \mu_H^2\,\delta(y-\pi r_c)\right]\chi_n$$

$$\underline{=0}$$

$$\Rightarrow \chi_n = \frac{e^{2ky}}{N_n} J_\nu\left(x_n e^{k(y-\pi r_c)}\right) \qquad \left\{ \begin{array}{l} x_n = \text{'roots'} \\ m_n = x_n \underbrace{k\epsilon}_{\simeq 300\,\text{GeV}} \end{array} \right.$$

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

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

$\Rightarrow$ roots!

- <u>want</u> $\quad x_1 = i\,x_T, \quad x_{n>1}$ real

$\uparrow$

tachyon w/ $\quad \chi_T = \dfrac{e^{2ky}}{N_T} J_\nu\left(i\,x_T e^{k(y-\pi r_c)}\right)$

so that $\quad \underline{V(y) = v\,\chi_T(y)}$

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

$\xi \geq \xi_{1,2}$ (I) $\qquad$ on <u>one</u> side of these boundary x_1 is real (imaginary)...

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

$$\xi_1 = -\frac{1}{4\beta_H} \qquad\qquad \xi_2 = \frac{5-8\beta_H}{16\beta_H^2}$$

$\Rightarrow$ Scan parameter space for solutions ...
[find β_P plays no rôle]

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

$$v(y) = v \cdot \frac{e^{2ky}}{N} \cdot J_\nu\left(ix_T e^{k(y-\pi r_c)}\right)$$

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

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

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

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

W/Z masses

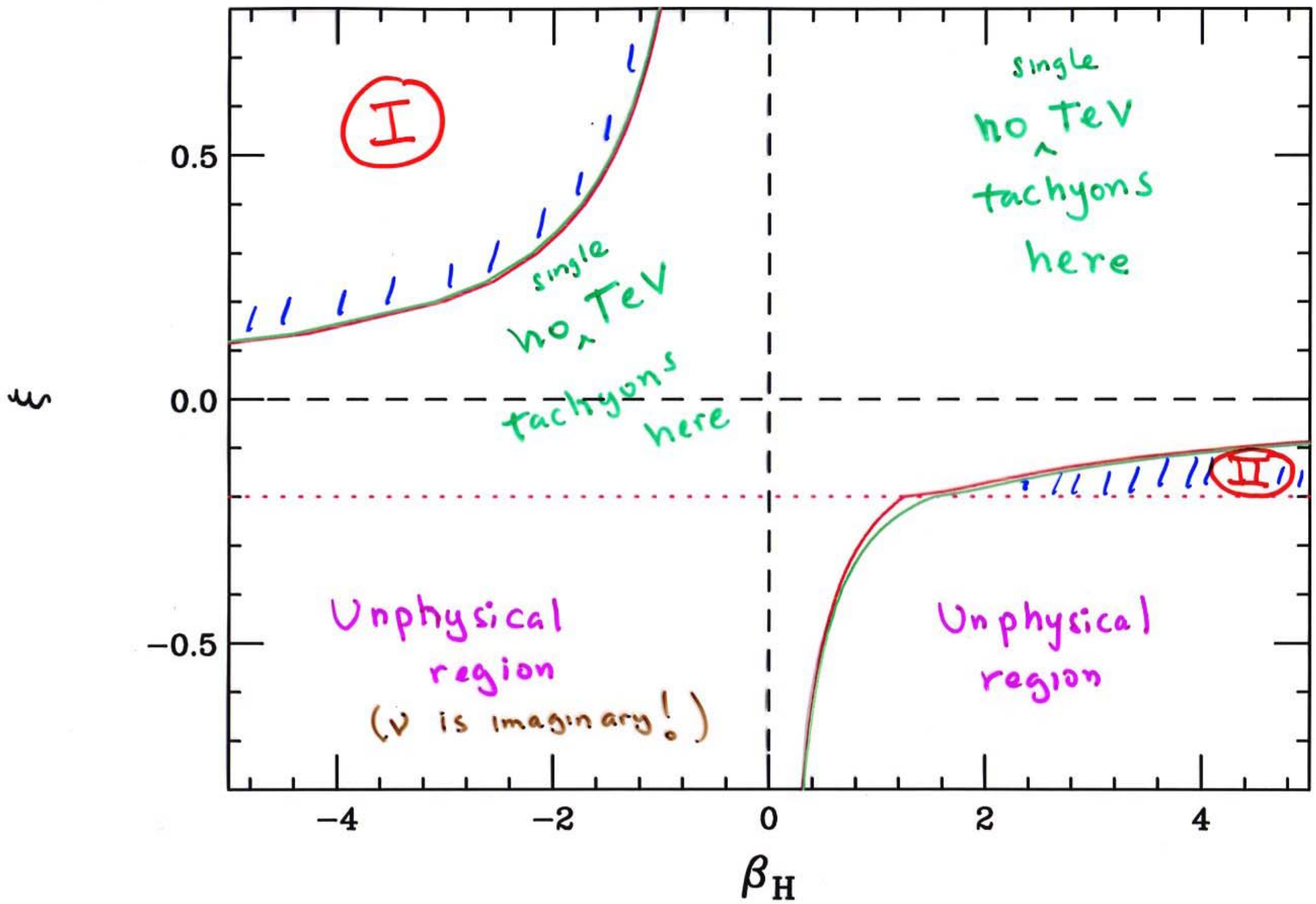
.. for the W $\quad \partial_y\left(e^{-2ky}\partial_y f_n^W\right) - \frac{1}{4} g_5^2 v^2(y) e^{-2ky} f_n^W + m_{n_W}^2 f_n = 0$

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

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

$\Rightarrow M_W = M_Z \cos\theta_W$ OK at ~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

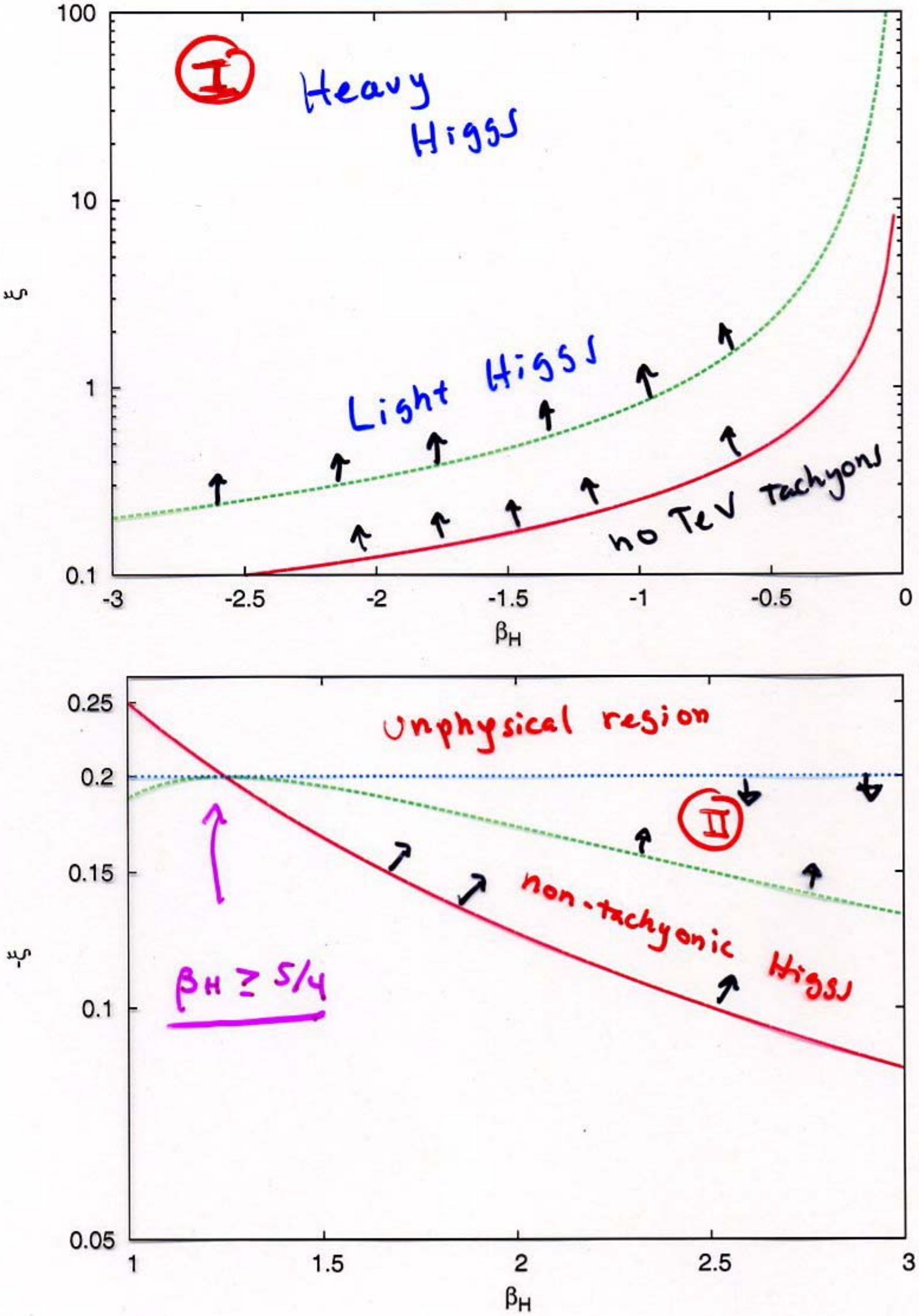


FIG. 1: Allowed regions in the $\xi - \beta_H$ plane for bulk Higgs induced EWSB in region I (top) and region II (bottom). The lower bound $\xi \geq -0.2$ (dotted blue) that insures $\nu^2 \geq 0$ in region II is also shown in addition to both constraints ξ_1 (dashed green) and ξ_2 (in solid red). The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

"light" Higgs constraint

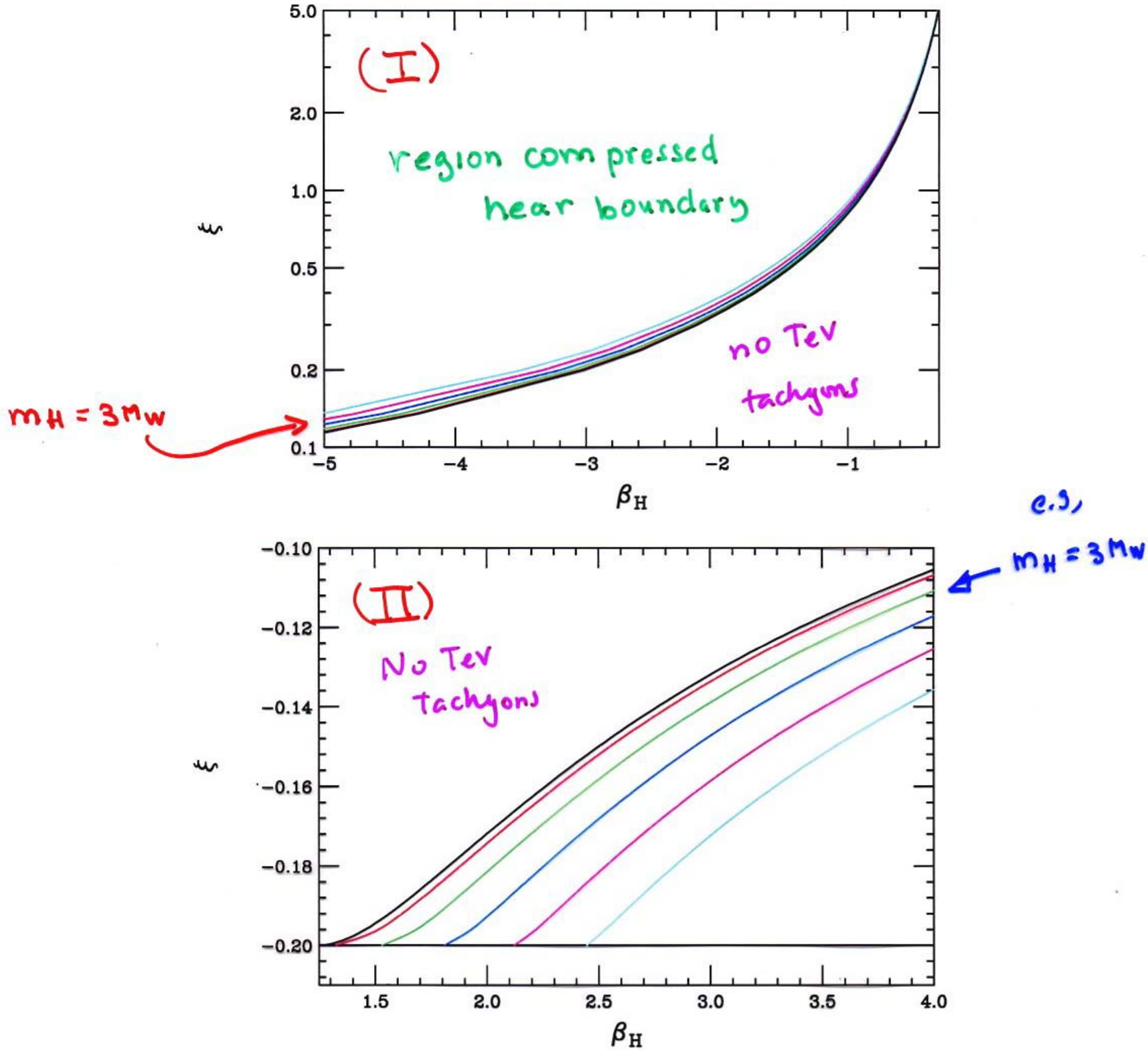
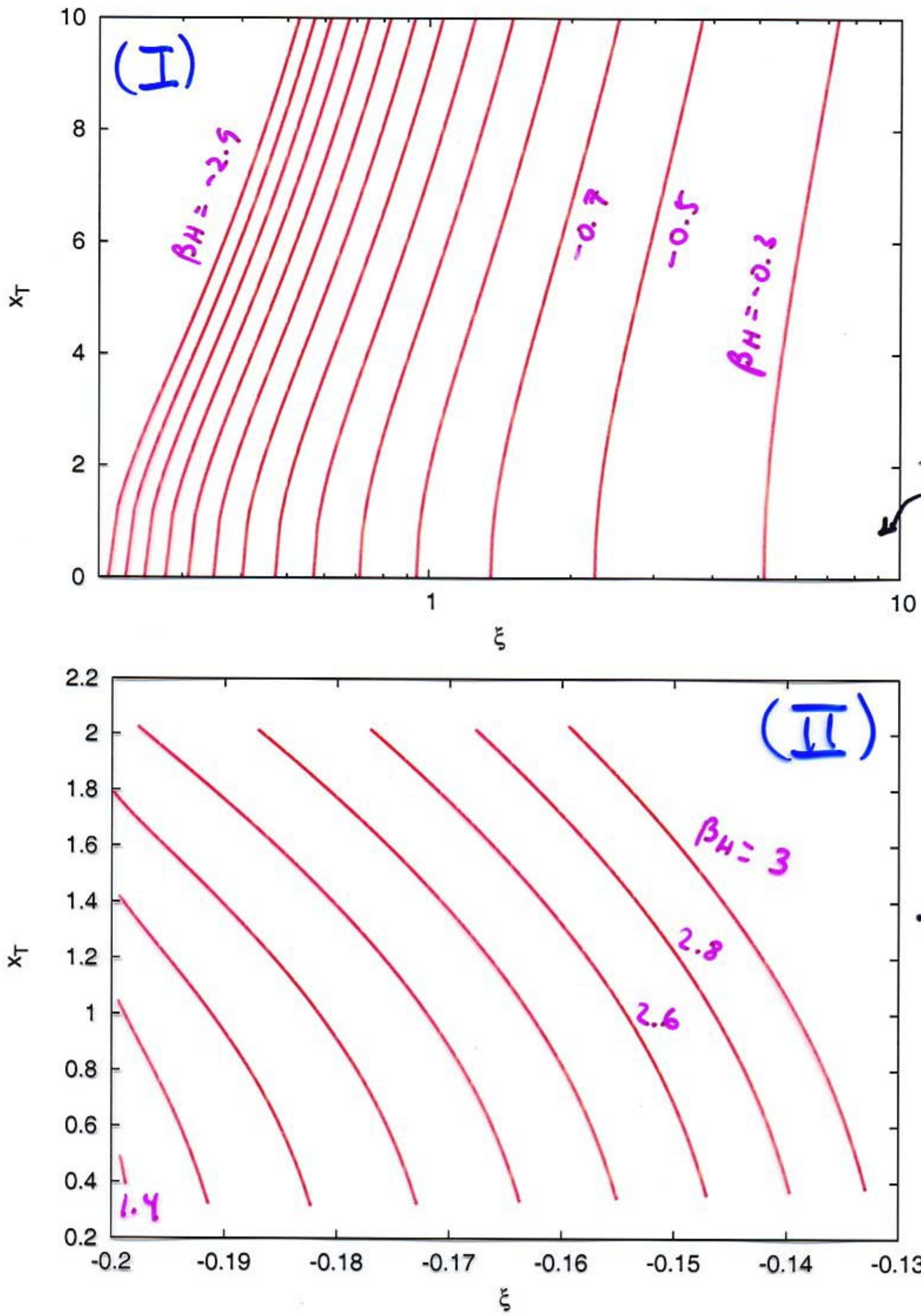


FIG. 3: The curves correspond to fixed tachyon root values, $x_T = 0$ (black) to 2.5 (cyan), in steps of 0.5, as functions of ξ and β_H in regions I (top) and II (bottom).

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



light Higgs prefered region

this is the prefered region for light Higgs masses

light Higgs region

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 'souces' 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 — induced wave-function curvature

related to WWH coupling $\Longleftrightarrow$ obviously reduced !

I II

$$\Rightarrow \boxed{\frac{g_{WWH}}{SM} \simeq \frac{1}{2} - \frac{2}{3}} \Leftarrow$$

- Higgs has (heavy) KK excitations ....

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

$\gtrsim$ 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}/SM for light Higgs

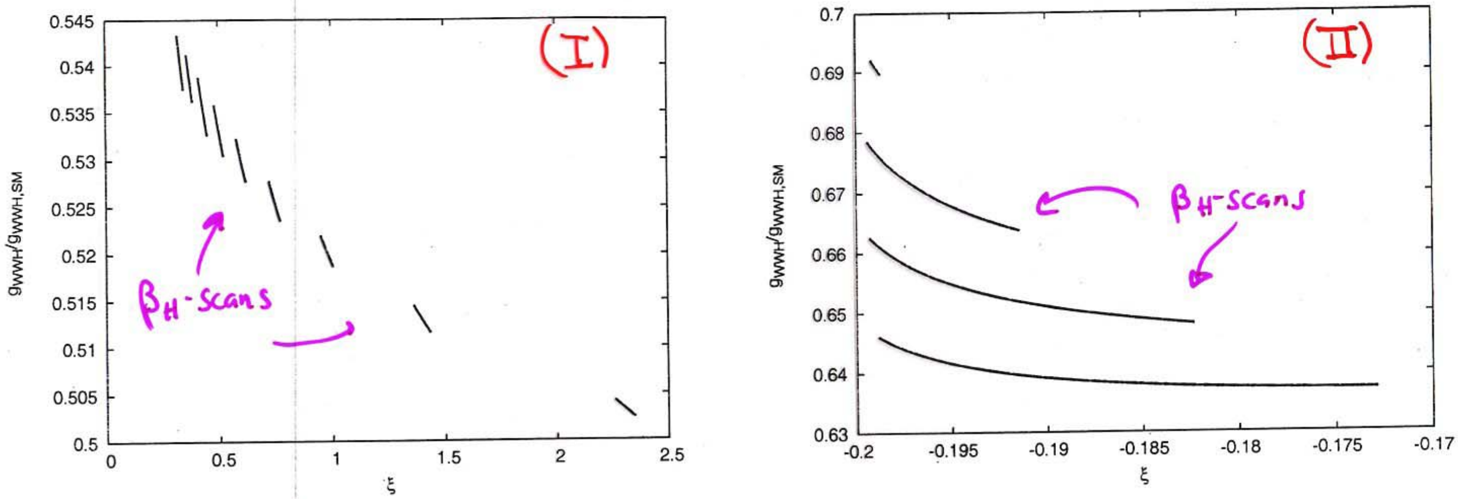
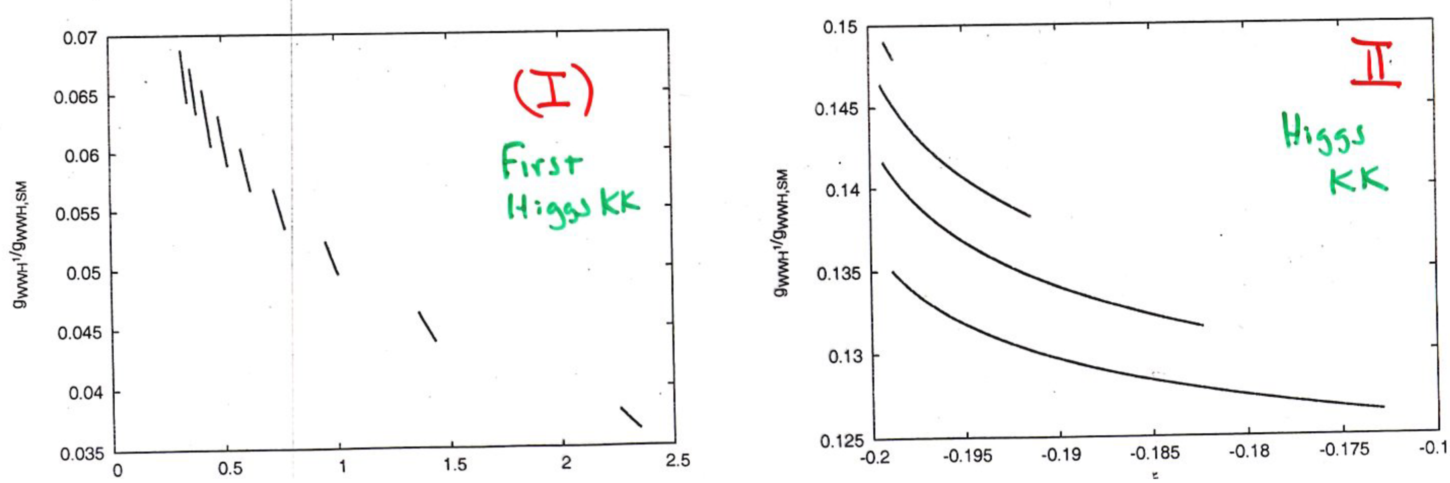


Figure 1: Values of the coupling ratio g_{WWH}/g_{WWH}^{SM} in regions I (left) and II (right) as functions of ξ for various β_H. In region I, from top from top to bottom, the curves correspond to $\beta_H = 1.4, 1.6, 1.8, 2.0$. A cut on the Higgs boson mass as described in the text has been imposed.



Higgs KK mass

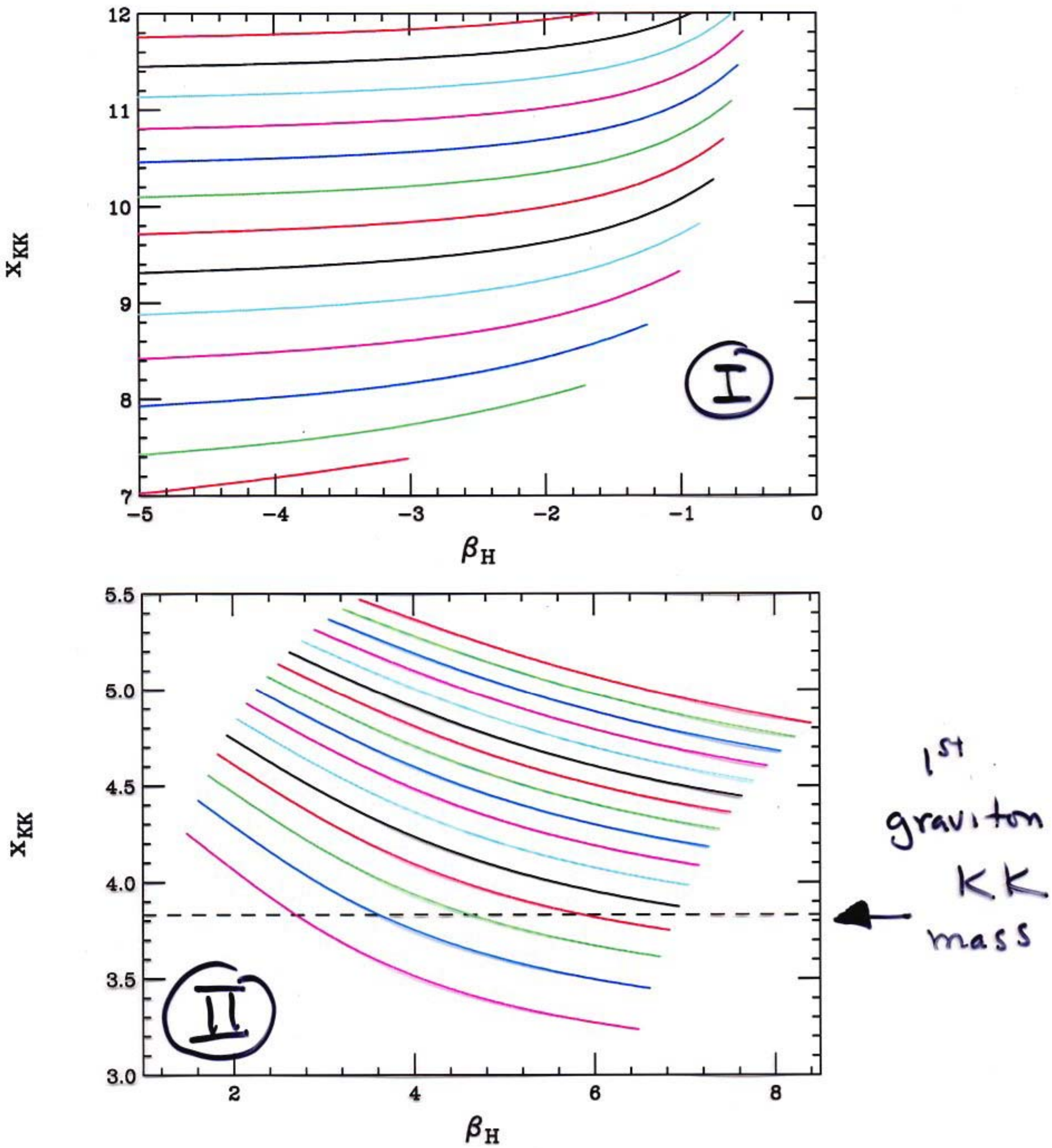


FIG. 4: Roots for the first Higgs KK excitation as a function of β_H for different values of ξ in regions I (top) and II (bottom). In region I, $\xi = 0.2$ is the lowest curve with ξ increasing by 0.2 for each subsequent curve. The curves are cut off on the right hand side by the ξ constraints. In region 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

$$S = S_{grav} + S_{Higgs} + S_{gauges}$$

string expansion

$$S_{grav} = \int d^5x \sqrt{-g} \left\{ \underbrace{\frac{M^3}{2} R - \Lambda_b}_{\text{usual RS}} + \frac{\alpha M}{2} \underbrace{\left(R^2 - 4 R_{AB} R^{AB} + R_{ABCD} R^{ABCD} \right)}_{\text{Gauss-Bonnet term}} \right.$$

$$\left. + \sum_i \left(\frac{M^3}{k} \gamma_i R_4 - \Lambda_i \right) \delta(y - y_i) \right\}$$

brane kinetic terms

Ricci scaler

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

"radion" term

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

$\rightarrow m^2 = 20k^2 \xi$ [radion mixing parameter !]

$\rightarrow \beta_H = 1 - \frac{4}{3} \alpha \frac{k^2}{M^2}$ GB parameter (<0)

"derived" from gravity

... naturally leads to region II w/ $\xi < 0$ + $\beta_H > 0$

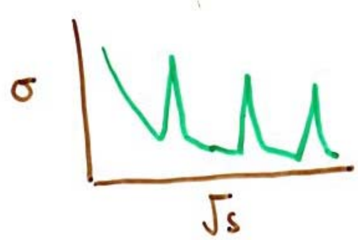
($|\alpha| \neq 0$!!)

→ 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, BF's, $G \to G_1 G_1$, ..

→ telbus: α, $\gamma_{0,\pi}$, Λ_π, $k\epsilon$, k/M, β_H, ...

compare parameter determinations from both sectors...

- Observe Higgs + radion

↳ m_{r_0}, β_H, ξ, ...

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

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 $\left(\frac{1}{2}-\frac{2}{3} \text{ of SM}\right)$
    - Higgs KK excitations $m^H_{KK} \approx m_{Grav}$
    - completely modified Higgs-radion sector
    - model parameters over determined by observations

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

plenty left to do...

∴ work now in progress..