New Directions in Randall-Sundrum Phenomenology

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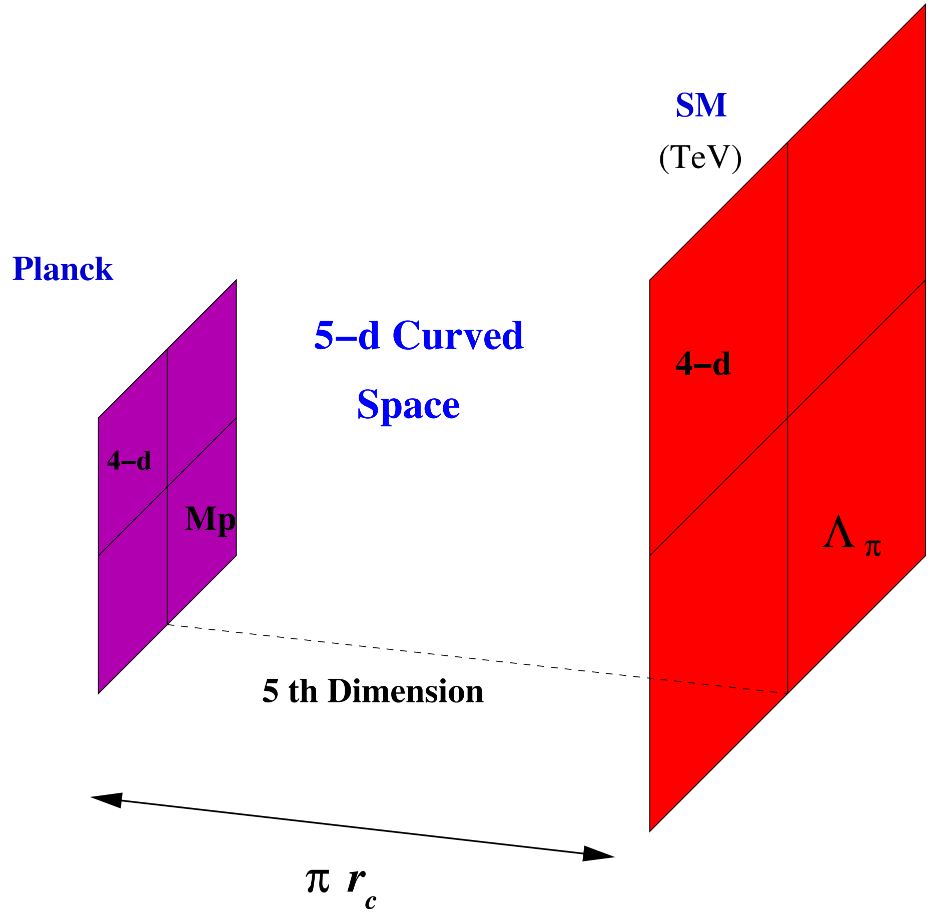
$SU(2)_L \times U(1)_Y$ Breaking

- $m_H^2 < 0 \Rightarrow \langle H \rangle \neq 0$; $m_W, m_Z \sim g\langle H \rangle$.
- $m_H \sim 100$ GeV $\ll M_P \sim 10^{18}$ GeV: Hierarchy; Beyond SM.

The Randall-Sundrum (RS) Model:

- $ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \quad ; \quad \sigma = k|y|$
- $-\pi r_c \leq y \leq \pi r_c \quad ; \quad \mathbb{Z}_2$ orbifold
- $M_5 \sim M_P$; $kr_c \sim 10$.
- $\Lambda_\pi = e^{-k\pi r_c} M_P \sim$ TeV.



Gravitational Redshift:

$\langle H \rangle_5 \sim M_P \rightarrow \langle H \rangle_4 \sim m_W$ on TeV-brane.

The Usual Picture:

- SM$-\{H\}$ could be in the bulk.

- $H \in$ TeV-brane to solve hierarchy.

Bulk Higgs with Constant 5-d vev:

(i) $m_W, mZ \rightarrow$ Extreme fine-tuning. (Chang, Hisano, Nakano, Okada, Yamaguchi, 1999)

(Huber, Sahfi, 2000)

(ii) Phenomenological problems. (H.D., Hewett, Rizzo, 2000)

Recent Work: Consistent EWSB with Bulk Higgs

(H.D., Lillie, Rizzo, 2005)

SM gauge and Higgs fields in 5-d:

$$\begin{aligned} S_{Higgs} &= \int d^5x \, \sqrt{-g} \left[(D^A\Phi)^\dagger (D_A\Phi) - m^2 \Phi^\dagger\Phi \right] - \\ & \int d^5x \, \sqrt{-g} \left\{ \left[\frac{\mu_H^2}{k} + \frac{\lambda_H}{k^2} \Phi^\dagger\Phi \right] \delta(y - \pi r_c) - \left[\frac{\mu_P^2}{k} - \frac{\lambda_P}{k^2} \Phi^\dagger\Phi \right] \delta(y) \right\} \Phi^\dagger\Phi \end{aligned}$$

$m^2 = 20k^2\xi \quad ; \quad \mu_P^2 = 16k^2\xi\beta_P \quad ; \quad \mu_H^2 = 16k^2\xi\beta_H.$

Bulk quartic $\lambda_5(\Phi^\dagger\Phi)^2$:

- Dim-6 in 5-d.
- Not required by gauge invariance.

$\Rightarrow$ We set $\lambda_5 = 0$.

We consider the free field: $\phi \to \sum_n \phi_n(x)\chi_n(y)$

$$\partial_y\left(e^{-4\sigma}\partial_y\chi_n\right) - m^2 e^{-4\sigma}\chi_n + \frac{1}{k}e^{-4\sigma}[\mu_P^2\delta(y) - \mu_H^2\delta(y-\pi r_c)]\chi_n + m_n^2 e^{-2\sigma}\chi_n = 0.$$

$$\Rightarrow \chi_n = \frac{e^{2\sigma}}{N_n}\zeta_\nu\left(x_n\epsilon e^{\sigma}\right)$$

$\zeta_\nu = J_\nu + \kappa_n Y_\nu$

$m_n = x_n k\epsilon$, $\epsilon = e^{-\pi k r_c} \simeq 10^{-16}$

$\nu^2 = 4 + m^2/k^2 = 4 + 20\xi.$

We want only one TeV-scale Higgs tachyon.

Find only one $x_T^2 < 0$, $|x_T| \sim 1$.

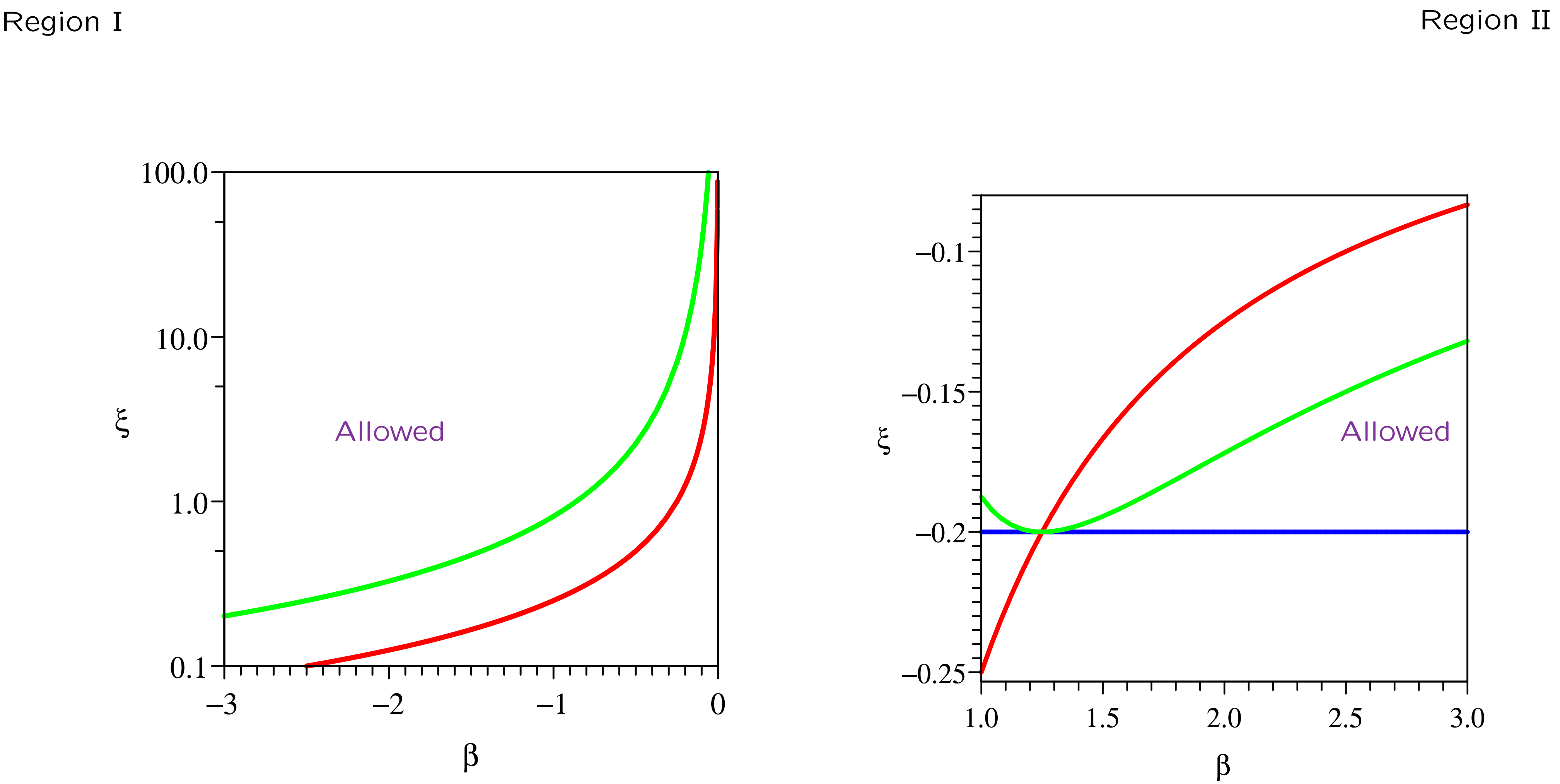
Parameter Space:

- Dependence on $\beta_P \sim \epsilon^{2\nu}$; ignored.
- Our analysis focused on (ξ, β_H).
- $\xi\beta_H > 0$ $(\mu_H^2 > 0)$ $\rightarrow$ No tachyons or $m_T \sim M_P$. $(m_T \sim m_H)$
- Explore:

Region (I) $\quad \xi > 0,\ \beta_H < 0$

Region (II) $\quad \xi < 0,\ \beta_H > 0$

- $\nu^2 \leq 0$: multiple tachyons, extreme parameter sensitivity *(instability)*.


Region I
Region II
100.0
10.0
1.0
0.1
ξ
Allowed
−3
−2
−1
0
β
−0.1
−0.15
−0.2
−0.25
ξ
Allowed
1.0
1.5
2.0
2.5
3.0
β

4-$\boldsymbol{d}$ Effective Theory:

$x_T^2 < 0 \Rightarrow \quad V = -m_T^2 \phi_T^\dagger \phi_T + \lambda_4 (\phi_T^\dagger \phi_T)^2$

$\lambda_4 = \frac{\lambda_H}{k^2} \int dy \sqrt{-g}\ \chi_T^4(y) \delta(y - \pi r_c)$

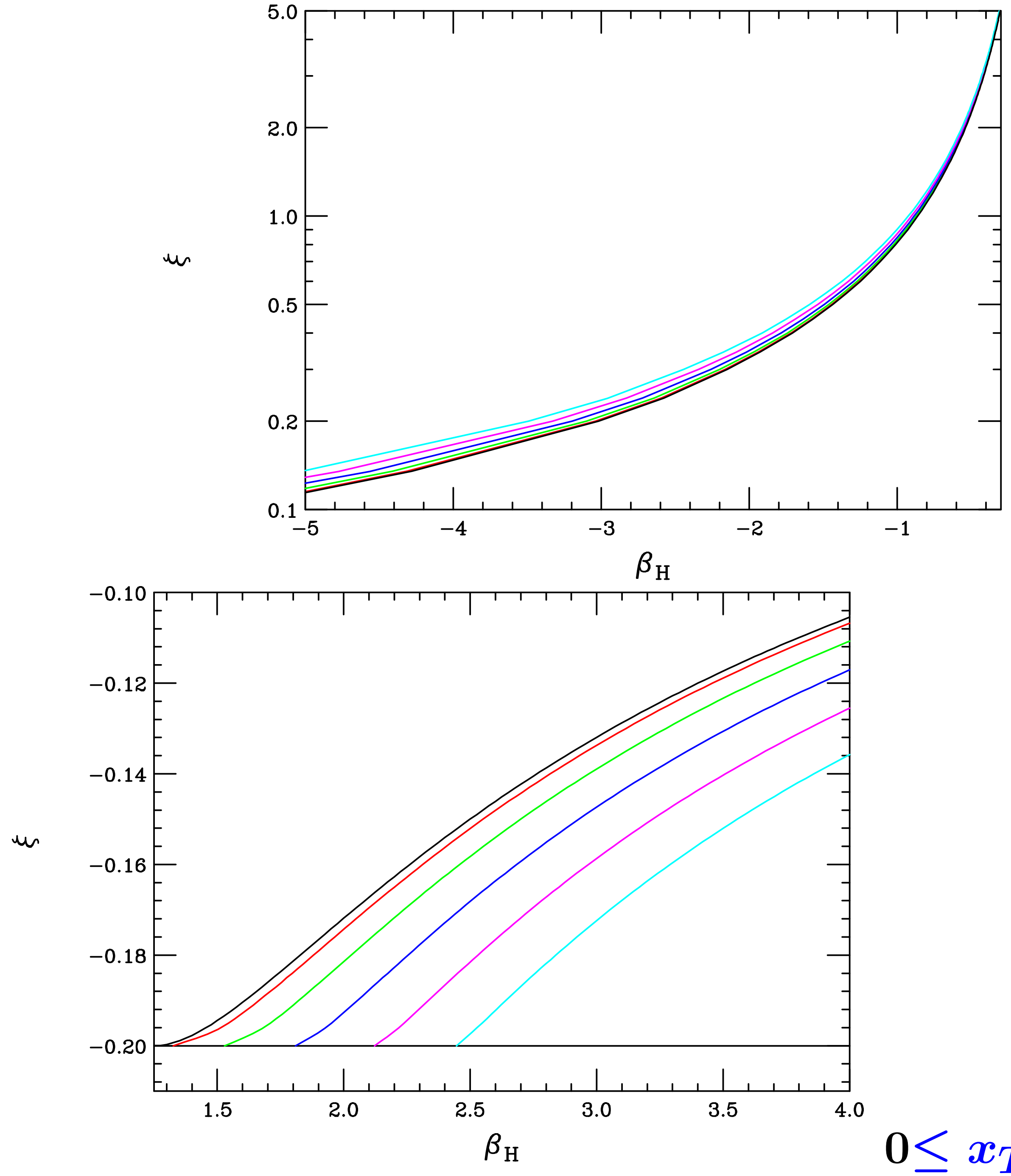
$\phi_T \to (v + H)/\sqrt{2}$

- $m_H = \sqrt{2} m_T = \sqrt{2} x_T k \epsilon$

- Higgs vev: profile in 5-d, $\chi_T \sim e^{(2+\nu)\sigma}$.

χ_T **`peaked near TeV-brane`** $\Rightarrow$ $v \sim$ **`TeV.`**

- χ_T is adjustable via (ξ, β_H); *model-building possibilities.*



$0 \leq x_T \leq 2.5$

Gauge Boson Masses

- $(D_A\Phi)^\dagger(D^A\Phi) \to m_W^2, m_Z^2$.
- $\partial_y\Big(e^{-2\sigma}\partial_y f_n\Big) - \frac{1}{4}g_5^2 v^2 \chi_T^2 e^{-2\sigma} f_n + m_n^2 f_n = 0.$ $\quad$ (g_5: 5-d $SU(2)_L$; v: 4-d)
- $\chi_T^2 \sim e^{2(\nu+2)\sigma} \Rightarrow \chi_T^2 \to \lambda\epsilon^{-2}\delta(y-\pi r_c)$.
- Perturbation $\oplus$ Variation of λ: $V_{pt} = \frac{1}{4}g_5^2 v^2\Big[\chi_T^2 e^{-2\sigma} - \lambda\delta(y-\pi r_c)\Big]$
- x_W: $m_W = x_w k\epsilon$; $x_W \simeq 0.2 - 0.25$.

$\Rightarrow$ $k\epsilon \sim 350$ GeV; $m_H \simeq 500$ GeV ($x_T = 1$).

- We find $\delta\rho \sim 5 - 10\%$.
- A more realistic setup may require $5-d$ $SU(2)_L \times SU(2)_R$.

Gravity-Induced EWSB

$$S_{bulk} = \int d^5x\, \sqrt{-g}\left[\frac{M^3}{2}R - \Lambda_b + \frac{\alpha M}{2}\Big(R^2 - 4R_{AB}R^{AB} + R_{ABCD}R^{ABCD}\Big)\right]$$

$$S_{branes} = \sum_{branes}\int d^5x\, \sqrt{-g}\left[\frac{M^3}{k}\gamma_i R_4 - \Lambda_i - \frac{\lambda_i}{k^2}(\Phi^\dagger\Phi)^2\right]\delta(y-y_i)$$

$$S_{Higgs} = \int d^5x\, \sqrt{-g}\left[(D^A\Phi)^\dagger(D_A\Phi) + \xi R\Phi^\dagger\Phi\right],$$

- $\langle R\rangle = -20k^2 + 16k[\delta(y) - \delta(y-\pi r_c)]$: $\beta_H = \beta_P = 1$.
- Gauss-Bonnet term:

$\Lambda_{Planck} = -\Lambda_{TeV} = 6kM^3\left(1 - \frac{4\alpha k^2}{3M^2}\right) \equiv 6kM^3\beta_H\,.$ (Kim, Kyae, Lee, 2000)

- $m^2 = 20k^2\xi$, $\mu^2 = 16k^2\xi\beta_H$; allowed parameter space as before.
- No radion, graviton KK ghosts: region II favored.

$\xi \approx \xi_c \quad ; \quad \xi_c = -3/16$ conformal.

Experimental Signatures

- Higgs KK states, $m_{KK} \lesssim 1 - 1.5$ TeV.

- $g_{WWH_1}/g^{SM}_{WWH} \simeq 0.02 - 0.13$; perhaps beyond LHC, may need CLIC.

- $g_{WWH}/g^{SM}_{WWH} \simeq 0.45 - 0.70$: measurable at ILC, likely LHC.

- Expect $H_1 t\bar{t}$-coupling large:

$\Rightarrow$ H_1 in $gg/\gamma\gamma$-fusion.

- $\lambda_{eff_1}/\lambda_{SM} \simeq 0.65 - 0.91$: Br$(H_1 \to HH)$ sizable.

- Gravity-Induced EWSB: LHC/ILC or CLIC-type measurements.

$\Rightarrow$ Correlations among the gravity and Higgs sector observables.

Conclusions

- Resolving $\langle H \rangle / M_P$ in RS does not necessitate Higgs on the wall.
- Suitable bulk/brane potentials for the Higgs give realistic EWSB in 4-d.
- Bulk Higgs: KK states of H and their phenomenology.
- $\langle H \rangle$ profile in 5-d: new model-building possibilities.
- Gravity-induced EWSB: possible with *off-the-wall Higgs*.
- Presicion multi-TeV measurements: Higgs-gravity connection.