Off-the-wall Higgs in the Randall-Sundrum model

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Davoudiasl, Lillie, and Rizzo  hep-ph/0509160
Outline

• Introduction
• Formalism
• Gravity induced EWSB
• Collider issues
• Conclusion
The Randall-Sundrum Model
Randall and Sundrum hep-ph/9905221

Slice of AdS$_5$, with metric

$$ds^2 = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$$

warp factor \quad coordinate of extra dimension

$$\sigma = k|y|$$

AdS curvature, $O(M_{Pl})$

Masses get scaled by $M \rightarrow Me^{-\pi kr_c}$

Solves the hierarchy problem for $kr_c \sim 11$

Can also:
- explain fermion mass hierarchy
- unify gauge couplings
- provide a dark matter candidate
Standard Model fields

On TeV brane \( \Rightarrow \) large 4-fermi operators: \( \frac{\lambda}{\Lambda^2_{\text{TeV}}} \psi \bar{\psi} \psi \bar{\psi} \).

Solution to Hierarchy problem \( \Rightarrow \) need to leave Higgs on TeV brane.

Also phenomenological problems with Higgs in bulk

Davoudiasl, Hewett, Rizzo  hep-ph/0006041

Can move fermions to Planck brane \( \Rightarrow \) 4-fermi operators supressed by \( M_{Pl} \).

But EWSB on TeV brane \( \Rightarrow \) fermions in bulk \( \Rightarrow \) gauges in bulk.

Gauge bosons in the bulk can lead to gauge coupling unification

Standard Model fields

On TeV brane $\Rightarrow$ large 4-fermi operators: $\frac{\lambda}{\Lambda_{\text{TeV}}^2} \psi \bar{\psi} \psi \bar{\psi}$.

Solution to Hierarchy problem $\Rightarrow$ need to leave Higgs on TeV brane.

Also phenomenological problems with Higgs in bulk

Need to leave EWSB on TeV brane

Can move fermions to Planck brane $\Rightarrow$ 4-fermi operators supressed by $M_{Pl}$.

But EWSB on TeV brane $\Rightarrow$ fermions in bulk $\Rightarrow$ gauges in bulk.

Gauge bosons in the bulk can lead to gauge coupling unification
Higgs sector

Promote to a bulk field with action

\[ S_{Higgs} = \int d^5x \sqrt{-g} \left[ (D^A\Phi)^\dagger (D_A\Phi) - \lambda_5\Phi^\dagger\Phi^2 - \left( m^2 + \frac{\mu_H^2}{k} \delta(y - \pi r_c) - \frac{\mu_P^2}{k} \delta(y) \right) \Phi^\dagger\Phi \right] \]

Ignore gauge parts and look at just the neutral mode

\[ S_{\text{trunc}} = \int d^5x \sqrt{-g} \left[ (\partial^A\phi)^\dagger (\partial_A\phi) - m^2 \phi^\dagger\phi + \frac{1}{k} \phi^\dagger\phi \left[ \mu_P^2 \delta(y) - \mu_H^2 \delta(y - \pi r_c) \right] \right] \]

Define:

\[ m^2 = 20k^2\xi \quad \mu_{P,H}^2 = 16k^2\xi \beta_{P,H} \]
Equations of motion

Usual KK reduction: \( \phi \to \sum_n \phi_n(x) \chi_n(y) \)

Gives equation of motion:

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

Solutions are the familiar

\[
\chi_n = \frac{e^{2\sigma}}{N_n} \zeta_\nu \left( x_n e^{\sigma} \right)
\]

\[
\zeta_\nu = J_\nu + \kappa_n Y_\nu
\]

Index is:

\[
\nu^2 = 4 + \frac{m^2}{k^2} = 4 + 20\xi
\]

set by boundary conditions

\[
\kappa_n \sim e^{-2\nu \pi kr_c}
\]

root set by b.c.s, given by:

\[
\left[ 2 \left( 1 + \frac{\mu_H^2}{4k^2} \right) - \nu \right] \zeta_\nu(x_n) + x_n \zeta_{\nu-1}(x_n) = 0
\]
Tachyonic solutions

We need $\xi \beta_H$ (i.e. $\mu_H$) negative, otherwise no tachyon, or Planck scale tachyon

Gives two regions:

Look for zeros of the root equation, gives:

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

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

Wavefunction is localized near IR-brane:

$$\chi_T \sim e^{(2+\nu)\sigma}$$

Approximation gets better as: $\nu \to \infty$
Allowed regions – single tachyon

Imaginary index
Wavefunction is localized near IR-brane:
\[ \chi_T \sim e^{(2+\nu)\sigma} \]

Approximation gets better as: \( \nu \to \infty \)
Tachyon root, cont.
Gauge boson masses

Gauge equation of motion:

\[ \partial_y \left( e^{-2\sigma} \partial_y f_n \right) - \frac{1}{4} g_5^2 v^2 \chi_T^2 e^{-2\sigma} f_n + m_n^2 f_n = 0 \]

Bessel function source! (Yikes!)

Find solution perturbatively. Start with: \[ \chi_T \sim e^{(2+\nu)\sigma} \]

\[ \chi_T^2 \rightarrow \lambda e^{-2\delta(y - \pi r_c)} \] (solutions known)

Then use perturbing potential:

\[ V_{pt} = \frac{1}{4} g_5^2 v^2 \left[ \chi_T^2 e^{-2\sigma} \lambda \delta(y - \pi r_c) \right] \]

variational parameter

Use this to calculate first-order mass matrix
Gauge boson masses, cont.

Vary $\lambda$ to minimize off-diagonal terms in mass matrix

We find: $\lambda \approx 1.1 - 1.3$ (Tells us delta function is reasonable approx)

Use this to calculate: $x_W \sim 0.20 - 0.25$

$$m_H = \sqrt{2} x_T / x_W M_W$$

Tells us we want $x_T \sim 0.5$

$m_H \lesssim 250 GeV$

We can also estimate EW parameters: $\rho \simeq 5 - 10\%$ (oops!)

Note: we haven't put in custodial $SU(2)$ (possible help with) $Z \rightarrow b\bar{b}$?

More work to be done!
Gravity-induced EWSB

Crucial observation, we can write:

\[ \xi R \Phi \dagger \Phi \]

and

\[ \langle R \rangle = -20k^2 + 16k[\delta(y) - \delta(y - \pi r_c)] \]

Can we use this to break Electroweak symmetry?

Not quite.

Sign is wrong. With this setup, we get a Planck scale vev.

See also Farakos and Pasipoularides hep-th/0504014, Falachi and Toms hep-th/0007025

But...
Expanded gravity/scalar action

\[ S = S_{\text{bulk}} + S_{\text{branes}} + S_{\text{Higgs}} + S_{\text{gauge}} \]

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

\[ S_{\text{branes}} = \sum_{\text{branes}} \int d^5x \sqrt{-g} \left[ \frac{M^3}{k} \gamma_i R_A - \Lambda_i \right] \delta(y - y_i) \]

Modifies standard RS solution

\[ \Lambda_{\text{Planck}} = -\Lambda_{\text{TeV}} = 6kM^3 \left( 1 - \frac{4\alpha k^2}{3M^2} \right) \equiv 6kM^3\beta_H \]

Then:

\[ S_{\text{Higgs}} = \int d^5x \sqrt{-g} \left[ (D^A\Phi)^\dagger (D_A\Phi) - \lambda_{5\Phi}(\Phi^\dagger \Phi)^2 + \xi R\Phi^\dagger \Phi \right] \]

produces

\[ S_{\text{eff}} = \int d^5x \sqrt{-g} \left[ (\partial^A\Phi)^\dagger (\partial_A\Phi) - m^2(\Phi^\dagger \Phi) + \frac{\mu^2}{k} \Phi^\dagger \Phi [\delta(y) - \delta(y - \pi r_c)] \right] \]

Massless Higgs?

\[ \xi R \Phi \Phi \]

Conformal coupling in 5D

\[ \xi = -\frac{3}{16} \]
Stability

Expand the metric to study the radion mode

\[ ds^2 = e^{-2\sigma - 2F} \eta_{\mu\nu} dx^\mu dx^\nu - [1 + 2F]^2 dy^2 \]

\[ F = e^{2\sigma} r_0(x) \]

Extracting the radion kinetic term to look for ghosts

\[ \frac{6 M^3}{k^3} (\partial r_0)^2 N^2_r = \left( 1 - 4\alpha \frac{k^2}{M^2} \right) (1 - 2\Omega_\pi) \]

\[ \Omega_{0,\pi} \equiv \frac{4\alpha k^2/M^2 \pm \gamma_{0,\pi}}{1 - 4\alpha k^2/M^2} \]

Similarly for gravitons

\[ \frac{M^5}{M_{Pl}^3} = \frac{M^3}{k^3} N^2_g \]

\[ N^2_g = \left( 1 - 4\alpha \frac{k^2}{M^2} \right) (1 + 2\Omega_0) + \frac{\xi k^2}{M^3 \epsilon^2} \]

No tachyons in gravity sector \( \Omega_\pi < 0 \)

Region I, out. Region II, good.

Csaki, Graesser, and Kribs, hep-th/0008151
Higgs-radion mixing

Match onto standard mixing Lagrangian:

\[ \mathcal{L} = -\frac{1}{2} H_n \Box H_n - \frac{1}{2} m_{H_n}^2 H_n^2 - \frac{1}{2} m_r^2 r^2 + \xi \gamma A_n H_n \Box r - \frac{1}{2} \left[ 1 + B \xi \gamma^2 \right] r \Box r \]

\[ \gamma = \frac{v}{\sqrt{6 \Lambda_\pi}} \]

'2' instead of '6'

\[ A_T = 2 e^2 N \int dy \, \chi_T^2 \simeq 2N \]
\[ A_i = 2 e^2 N \int dy \, \chi_T \chi_i \simeq 0 \]
\[ B = -6 e^4 N^2 \int dy \, e^{2k|y|} \chi_T^2 \simeq -6N^2 \]

Avoiding ghosts gives the constraint:

\[ \frac{B}{2A_n^2} \left[ 1 + \left( 1 + \frac{4A_n^2}{\gamma^2 B^2} \right)^{1/2} \right] \leq \xi \leq \frac{B}{2A_n^2} \left[ 1 - \left( 1 + \frac{4A_n^2}{\gamma^2 B^2} \right)^{1/2} \right] \]

Easily satisfied

Note \( \xi \) allowed a larger range than brane case
Collider issues

Best signal for bulk Higgs: find a KK

Problem: generally too heavy \( \sim 30 - 100(15 - 30) M_W \) (low end is \( \sim 1.2 \text{ TeV} \))

Might be accessible to a multi-TeV linear collider, possibly a photon collider

Also, couplings are reduced:

\[
S_{\text{eff}} = \int d^4x \sum_n H_n W^a_{\mu} W^{\mu a} \frac{1}{2} g_5^2 v \int dy \ e^{-2\sigma} \chi_T \chi_n f_0^2
\]

\[
S'_{\text{eff}} = \sum_n \lambda_{\text{eff,n}} \int d^4x \ (3vH^2 + H^3) H_n
\]

\[
\lambda_{\text{SM}} = \lambda_5 \Phi \int dy \ \sqrt{-g} \chi_T^4
\]

\[
\lambda_{\text{eff,n}} = \lambda_{\text{SM}} \frac{\int dy \ \sqrt{-g} \chi_T^3 \chi_n}{\int dy \ \sqrt{-g} \chi_T^4}
\]
First Higgs KK

$x_W \sim 0.2$

Graviton root
$H_1W$ Coupling

$x_W \sim 0.2$
Collider issues, cont.

HWW couplings are reduced

\[ M_W^2 = \frac{1}{4} g_\sigma^2 v^2 \int dy \ e^{-2\sigma} f_0^2 \chi_T^2 + \int dy \ e^{-2\sigma} (\partial_y f_0)^2 \]

Not unique to a bulk Higgs

Can be directly measured at the ILC
Corrections to Higgs physics

- Gauge higgs coupling suppressed
- Fermion KK states coupling to Higgs enhanced by $\sqrt{2\log(R'/R)}$
- Expect enhancements to $gg \rightarrow h$
- Shifts to $h \rightarrow \gamma\gamma$

LEP Higgs working group
Testing gravity-induced EWSB

There are correlations between Higgs and gravity sectors

Test by over-constraining from data

Extract $\xi$ and other mixing parameters from Higgs and radion sector

From gravity sector can obtain $\alpha, \gamma_{0,\pi}, \Lambda_\pi, k/M$

Comes from masses, widths, and decays of $G_1, G_2, G_3$

Together these predict a Higgs mass

However....
Graviton coupling to light fermions Planck suppressed

Coupling to gauge bosons volume suppressed

Need to find another channel: top? Higgs?
Conclusions

• There is a phenomenologically viable model where the Higgs is a bulk field

• Electroweak symmetry can be broken by gravitational effects

• Difficult to identify at colliders?
Drell-Yan

Different widths to account for fermion location

Generically will be lighter than studied here
Dijet resonances

Check out the scale!

Of course, gluons are also in the bulk
$W_L^\pm Z_L \rightarrow W_L^\pm Z_L$

- Luminosity: $300 \text{ fb}^{-1}$
- $E_j > 300 \text{ GeV}$
- $p_{T,j} > 30 \text{ GeV}$
- $2.0 < |\eta_j| < 4.5$
- $|\eta_1| < 2.5$

Birkedal, Matchev, and Perelstein hep-ph/0412278
Loop processes