EW constraints on warped scenarios with custodial protection

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Based on work with M. Carena, J. Santiago and C. Wagner
The RS scenario: scales

Randall-Sundrum proposal (1999)

Slice of AdS: \( ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2 \) \( y \in [0, L] \)

Non-supersymmetric solution to the hierarchy problem

Multiple scales through localization along the 5th dimension

EW symmetry breaking on IR brane \( \rightarrow \) "TeV scale"

Delocalized SM fermions as a solution to RS1 flavor problem

- Suppression of FCNC's due to higher dimension operators
- SM fermion mass hierarchies (exponential hierarchies natural)
The RS scenario and EWSB

New physics at a scale of order \( \tilde{k} \equiv k e^{-kL} \), although radiative corrections to Higgs potential generically cutoff at \( \Lambda \gg \tilde{k} \)

\[ \longrightarrow \text{little hierarchy problem: why } m_h^2 \ll \Lambda^2? \]

However, in a "gauge-Higgs unification" scenario, i.e. Higgs as \( A_5 \), loop contributions to \( m_h \) are really cutoff at \( \tilde{k} \)

In fact, Higgs potential is calculable \( \longrightarrow \text{can explain EWSB!} \)
But how light the new physics?

Tree level corrections to SM observables $\rightarrow$ stringent constraints

Large contributions to oblique parameters, e.g. $T$

Shifts in fermion-gauge boson couplings

These constraints can put the new physics beyond the reach of the LHC

In this talk I will consider models that tame the large tree-level corrections by

- Imposing a custodial SU(2) symmetry (Agashe, Delgado, May, Sundrum)
- Quantum numbers such that bottom couplings are protected (Agashe, Contino, DaRold, Pomarol)

$S$ parameter remains as source of most important constraints...

... however, protected parameters can still be important
Custodial Symmetry: \( SU(2)_L \times SU(2)_R \)

Unlike in SM with Higgs doublet, large custodial violation due to KK of hypercharge and top quark: \( g' \sqrt{2kL} \) and \( y_t \sqrt{2kL} \) with \( \sqrt{2kL} \approx 8 \).

1. Possible solution: soften couplings with BKT' (Davoudiasl, Hewett and Rizzo) (Carena, Delgado, E.P., Tait and Wagner)

2. Make \( SU(2)_R \) exact:

\[ SU(2)_L \times SU(2)_R \times U(1)_X \]

... and brake it minimally (at UV brane only)

\[ U(1)_Y \]

\[
\begin{align*}
W^a_{L\mu} & \sim (+, +) , & B_\mu & \sim (+, +) & a = 1, 2, 3 \\
W^b_{R\mu} & \sim (-, +) , & Z'_\mu & \sim (-, +) & b = 1, 2 \\
B_\mu & = \frac{g_5 W^3_{R\mu} + g_5 X_\mu}{\sqrt{g_5^2 + g_5^2}} 
\end{align*}
\]

Custodial violation due to small KK-mode splittings: \( M_{W_L^n} \neq M_{W_R^n} \), \( g_{W_L^n} \neq g_{W_R^n} \)

Schematically, the T parameter at tree-level:

\[
\begin{align*}
W^{(0)} & \quad W_L \quad W^{(0)} & = \quad W^{(0)} & \quad W_R \quad W^{(0)} \\
\langle H \rangle & \quad \times & \quad \times & \quad \langle H \rangle & \quad \times & \quad \times \\
\Delta_{++} - \Delta_{--} & \approx 0 
\end{align*}
\]
The T-parameter at one-loop

Non-local breaking of custodial $SU(2) \rightarrow T \neq 0$, calculable

Types of contributions discussed by Agashe, Delgado, May, Sundrum

Gauge: (Schematic)

$W_\mu$ $W_\nu$ $W_\mu$ $W_\nu$ $\sim$ small

Fermions: $W_\mu$ $W_\nu$, $W^1_\mu$ $W^1_\nu$

These depend on various localization parameters!
Why one-loop interesting?

Localization towards IR brane → better custodial protection

But in SM, top gives (1-loop)

\[ T_{\text{top}} = \frac{N_c m_{\text{top}}^2}{16\pi s^2 c^2 m_Z^2} \sim 1 \]

→ Expect some degree of cancellation in this limit
New physics may contribute \( \Delta T < 0 \) (top sector)

Example: Simplest implementation of \( SU(2)_R \) in fermion sector

\( SU(2)_L \) doublet

\[ q_L = \begin{pmatrix} t_L(+) & b_L(+) \end{pmatrix} \]

\( SU(2)_R \) doublet

\[ Q_R = \begin{pmatrix} t_R(+) & b'_R(-+) \end{pmatrix} \]

\[ c_Q > 1/2 \]

\( b'_R \) ultralight

\( \Delta T < 0 \) (top sector)

Large corrections to \( Zb\bar{b} \) anyway!

(mixing of \( b_L \) and \( b'_R \))

\( m_{KK}^{\text{gauge}} > 9 \text{ TeV} \)
Coupling of Z to bottom and custodial protection

If $g_L = g_R$ and $T^3_L(b_L) = T^3_R(b_L)$:

\[ W_L b_L b_L - W_R b_L b_L = G^{b_L} - G^{b_L} \approx 0 \]

\[ SU(2)_R \]

\[ SU(2)_L \]

\[
\begin{pmatrix}
\chi^u_L(-, +) & q^+_L(+, +) \\
\chi^d_L(-, +) & q^b_L(+, +)
\end{pmatrix}
\sim (2, 2)_{2/3} \sim \begin{pmatrix} 5/3 & 2/3 \\ 2/3 & -1/3 \end{pmatrix}
\]

Impose discrete $P_{LR}$ and choose quantum numbers of $b_L$

(No counterterms that correct $Z b_L \bar{b}_L$ vertex allowed!)
T and custodial protection of $Z b_L \bar{b}_L$

When $Q_L = \left( \frac{\chi_L}{\chi_L^d} (-, +), \frac{q_L}{q_L^d} (+, +) \right) \oplus t_R (+, +)$, $b_R$ from $SU(2)$ triplets

Negative contribution: EWSB mixing of bidoublet KK modes with $t_R$

$\chi$'s lighter and more strongly coupled to Higgs than $q$'s

Positive $T$ from mixing with singlet!

Together with $S > 0 \rightarrow t_R$ far from IR brane seems preferred

Light singlet states that mix strongly with the top quark
Global fit to EW observables

(Carena, E.P., Santiago, Wagner)

We would like to address the following, in the context of the previous models:

- Localizing the light fermions near the "conformal" point can decouple the tower of KK modes of the SM gauge bosons
  
  \[ \text{Can one get rid of the bounds from the "S parameter"?} \]

- How important are the 1-loop contributions to $T$ and the $Zb_L\bar{b}_L$ vertex?

"S,T,U" analysis insufficient, global fit is required

(use Han, Skiba fit based on dim-6 ops)

Non-trivial constraints remain due to

- Couplings to $W_R$ non-universal
- Shifts in up- and down-type couplings different
- Positive $T$ preferred: constraints on localization parameters of 3rd generation quark sector

\[ \tilde{k} \equiv k e^{-k L} \gtrsim 1 \text{ TeV (95% C.L.)} \]
\[ \implies M_{K}^{\text{gauge}} \gtrsim 2.5 \text{ TeV} \]
Global fit to EW observables

- New measurements of $m_t$ and $m_W$ may generate some tension in SM
- Interestingly, tension relaxed in the presence of the new physics

Green region: predicted $m_W$ at 95% CL (global fit with $m_W$ excluded, $m_h = 115$ GeV)

- 68% C.L. based on combined CDF/D0 top mass, $m_t = 170.9 \pm 1.8$ GeV
- plus newest combined LEP and Tevatron measurement of $M_W = 80.398 \pm 0.025$ GeV

![Graph showing $m_W$ and $m_t$ relationships with various measurements and predictions.]
Application: Gauge-Higgs Unification

Bulk gauge symm: \( SU(3)_c \times SO(5) \times U(1)_X \rightarrow SO(5) \supset SU(2)_L \times SU(2)_R \)

UV: \( SU(2)_L \times U(1)_Y \)

IR: \( SO(4) \times U(1)_X \simeq SU(2)_L \times SU(2)_R \times U(1)_X \)

Extra gauge bosons have the quantum numbers of the Higgs

\[
SO(5)/SO(4) \rightarrow A^\alpha_\mu (-, -) \quad A^\alpha_5 (+, +)
\]

Identify with \( H \)

No tree-level Higgs potential \( \rightarrow \) induced at one-loop (calculable)

The fermion sector is more model dependent. Built out of

\[
5 \sim (2, 2) \oplus 1 \quad \text{and} \quad 10 \sim (2, 2) \oplus (3, 1) \oplus (1, 3)
\]

Since Yukawa’s \( \longleftrightarrow \) gauge coupling: flavour from IR localized mass terms

\[
\mathcal{L}_m = \delta (y - L) \left[ \bar{u}'_L \tilde{M}_u u_R + \bar{Q}'_1 M_u Q_2 R + \bar{Q}'_1 M_d Q_3 R + \text{h.c.} \right]
\]

Other parameters relevant the for EW fit:\[ c_L, c_R \] localization of \( 1^{st}, 2^{nd} \) gen.\[ c_1, c_2, c_3 \] localization of \( 3^{rd} \) gen.
The Higgs Potential

Coleman-Weinberg potential:

\[ V(h) = \sum_r \pm \frac{N_r}{(4\pi)^2} \int_0^\infty dp \, p^3 \log \rho(-p^2) \]

Quartic from top spectral function:

\[ \rho_t(z^2) = 1 + F_{t1}(z^2) \sin^2 \left( \frac{h}{\sqrt{2}f_h} \right) + F_{t2}(z^2) \sin^4 \left( \frac{h}{\sqrt{2}f_h} \right) \]

\[ f_h \propto \tilde{k}/\sqrt{k_L} \]

- Correct EWSB pattern (i.e. \(m_Z, m_W\)) for any \(c_1, c_2\)
- Correct top (and bottom) masses for either:
  - \(t_R\) mostly composite (\(c_2 \sim 0.4\))
  - \(t_R\) mostly fundamental (\(c_2 \sim -0.4\))
  - \(t_L\) cannot be very flat (\(|c_1| \leq 0.3\))
Consider "oblique region" with light fermions far from IR brane (fit unlikely to improve significantly in other regions)

Green region: EWSB, linear approx holds, correct $m_t, m_b, m_h$ above LEP bound, and $\tilde{k} < 2$ TeV ($M_{KK}^{gauge} < 5$ TeV)
Some properties of fermionic states

All points obey conditions of green region in previous two figures

Couplings to KK gluons of LH (t,b) comparable to those of RH top

Lightest KK fermion states

Couplings of $G'_\mu$ to 3rd gen. in units of $g_s$

- Light vector-like SM singlets (that can give $T > 0$)
- Exotic states can be light if they do not violate custodial symmetry (naturally present in gauge-Higgs scenarios)
  → degenerate vector-like fermions
Conclusions

• Possible to build fully realistic RS scenarios, that
  • pass EW constraints
  • have gauge boson KK resonances likely accessible at the LHC
  • require KK fermion resonances lighter than gauge KK modes
  • dynamical EW symmetry breaking

• Calculability at loop level can constraint the parameter space and suggest interesting consequences for the collider phenomenology:
  • Couplings of \((t_L, b_L)\) to new physics need not be suppressed compared to those of \(t_R\).
  • Lightest states likely to have a large singlet component
  • Lightest bidoublet KK fermion states likely to be fairly degenerate
  • Expect non-trivial decay chains of KK gluons
Details of fermion sector

The fermion sector is more model dependent. Built out of

\[ 5 \sim (2, 2) \oplus 1 \] \quad \text{and} \quad \[ 10 \sim (2, 2) \oplus (3, 1) \oplus (1, 3) \]

In gauge-Higgs unification scenarios Yukawa’s arise from gauge couplings. Flavour structure from mixing via IR localized mass terms

\[ \xi_{1L} \sim Q_{1L}^i = \begin{pmatrix} \chi_{1L}^{u_i}(-,+) & q_{\tilde{u}i}^L (+,+) \\ \chi_{1L}^{d_i}(-,+) & q_{\tilde{d}i}^L (+,+) \end{pmatrix} \oplus u_{L}^i(-,+) \]

\[ \xi_{2R} \sim Q_{2R}^i = \begin{pmatrix} \chi_{2R}^{u_i}(-,+) & q_{\tilde{u}i}^R (-,+) \\ \chi_{2R}^{d_i}(-,+) & q_{\tilde{d}i}^R (-,+) \end{pmatrix} \oplus u_{R}^i(+,+) \]

\[ \xi_{3R} \sim T_{1R}^i = \begin{pmatrix} \psi_{1R}^{u_i}(-,+) \\ U_{R}(-,+) \\ D_{R}^i(-,+) \end{pmatrix} \oplus T_{2R}^i = \begin{pmatrix} \psi_{2R}^{u_i}(-,+) \\ U_{R}(-,+) \\ D_{R}^i(+,+) \end{pmatrix} \oplus Q_{3R}^i = \begin{pmatrix} \chi_{3R}^{u_i}(-,+) & q_{\tilde{u}i}^R (-,+) \\ \chi_{3R}^{d_i}(-,+) & q_{\tilde{d}i}^R (-,+) \end{pmatrix} \]

\[ \mathcal{L}_m = \delta(y - L) \left[ \tilde{u}_L^i \tilde{M}_u u_R + \tilde{Q}_{1L} M_u Q_{2R} + \tilde{Q}_{1L} M_d Q_{3R} + h.c. \right] \]

Other parameters relevant for EW fit:

\[ c_L, c_R \] localization of 1\textsuperscript{st}, 2\textsuperscript{nd} gen.

\[ c_1, c_2, c_3 \] localization of 3\textsuperscript{rd} gen.
### Observables used in global fit
(bottom treated independently)

(Han, Skiba)

<table>
<thead>
<tr>
<th></th>
<th>Standard Notation</th>
<th>Measurement</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Atomic parity</td>
<td>$Q_{W}(Cs)$ $Q_{W}(Tl)$</td>
<td>Weak charge in Cs $Q_{W}(Tl)$</td>
<td>[21, 22]</td>
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<td>violation</td>
<td></td>
<td>$\nu_{\mu}$-nucleon scattering from NuTeV</td>
<td>[23]</td>
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<td>$\nu_{\mu}$-nucleon scattering from CDHS and CHARM</td>
<td>[24, 25]</td>
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<td>$\nu_{\mu}$-nucleon scattering from CCFR</td>
<td>[26]</td>
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<td>$\nu_e$ scattering from CHARM II</td>
<td>[27]</td>
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<tr>
<td>DIS</td>
<td>$g_{L}^{2}, g_{R}^{2}$ $R^{\nu}$</td>
<td>$\Gamma_{Z}$ $\sigma_{h}^{0}$ $R_{j}^{0}(f = e, \mu, \tau, b, c)$</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>$\kappa$ $g_{V}^{ue}, g_{A}^{ve}$</td>
<td>$A_{FB}^{0,f}(f = e, \mu, \tau, b, c)$ $\sin^{2}\theta_{eff}^{lep}(Q_{FB})$</td>
<td>[20]</td>
</tr>
<tr>
<td>Z-pole</td>
<td></td>
<td>$A_{f}(f = e, \mu, \tau, b, c)$ $A_{FB}^{f}(f = \mu, \tau)$</td>
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<td></td>
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<td>$\sigma_{f}(f = q, \mu, \tau)$ $d\sigma_{e}/d\cos\theta$</td>
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<td>$A_{FB}^{f}(f = \mu, \tau)$ $d\sigma_{W}/d\cos\theta$</td>
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<td></td>
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<td>$M_{W}$ W mass</td>
<td>[20, 30]</td>
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**TABLE I: Relevant measurements**