Warped extra-dimension paradigm: precision EW data & tests at ILC

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partly from...

C. Bouchart,
G.M. NPB 2008

A. Djouadi, G.M.,
F. Richard NPB 2007
I) Introduction

II) Comparison of EW fits in RS/SM

III) The case of heavy flavors

IV) Testing warped ED models at ILC

V) Conclusion
I) Introduction

Problems/Solutions in the Higgs boson sector

a) Quantum instability of the Higgs mass: \( \delta m_h^2 \propto \Lambda_{NP}^2 \)

\(~\Rightarrow\) Supersymmetry (MSSM): \( \delta m_h^2 \approx \tilde{m}^2 \approx (10^2 \text{ GeV})^2 \) as no quadratic dvg.

\(~\Rightarrow\) Extra Dimensions (ADD,RS): \( \delta m_h^2 \) protected by \( \Lambda_{NP} < M_{\text{grav}} \approx \text{TeV} \)

(Higgsless): models without Higgs boson!

\(~\Rightarrow\) Composite Higgs (MHCM): \( \delta m_h^2 \) protected by \( \Lambda_{NP} = \Lambda_{IR} \approx \text{TeV} \)

[& possibly till \( \Lambda_{NP} \) via a global symmetry]

b) Quantum instability of the Higgs quartic coupling \( \lambda \)

\(~\Rightarrow\) Supersymmetry (MSSM): SUSY \( \Rightarrow \lambda = g^2 \) protects \( \lambda \)

\(~\Rightarrow\) Extra Dimensions (gauge-Higgs unif.): GAUGE SYM. \( \Rightarrow \lambda = g^2 \) protects \( \lambda \)

(Higgsless): no high-energy Higgs potential
c) **EW Symmetry Breaking dynamics**

~> Supersymmetry (mSUGRA): EWSB triggered by negative Higgs mass induced radiatively (via top quark loop)

~> Composite Higgs (MHCM): EWSB triggered by negative Higgs mass induced radiatively (via top quark loop)

~> Extra Dimensions (Higgsless): SB by field Boundary Conditions & KK masses for fermions/bosons

**So the main approaches towards the Higgs questions are SUSY or ED like**

+ renew of interest for ED-type scenarios:

\[
\begin{align*}
\text{EXP.} & - \text{no discovery of superpartners @ LEP II (nor Tevatron Run II)} \\
\text{TH.} & - \text{AdS/CFT correspondence (98’)} \Rightarrow \text{calculability of EW observables (03’)} \\
& \text{in Composite Higgs scenarios (84’)}
\end{align*}
\]
+ other attractive features of the Extra-Dimension scenarios:

- WIMP candidates for the dark matter of universe (UED,RS) stable due to a KK-parity

- Unification of gauge couplings (ADD) at high-energies (RS)

- Fermion mass and flavor models (ADD,RS) in SUSY

- ED = necessary ingredient for high-energy string theories
Bulk gauge bosons/fermions mix with their KK excitations

=> tree-level contributions to EW observables

so the challenges are to...

[1] respect the constraints from EW precision data

=> Bulk custodial symmetry

\[
\begin{align*}
O(4) & \quad SU(2)_L \times SU(2)_R \\
\Downarrow & \quad \cong \quad \Downarrow \\
O(3) & \quad SU(2)_V \times P_{LR}
\end{align*}
\]

=> Brane-localized kinetic terms for fermions/gauge fields

[2] interpret anomalies in the SM fit of EW data (main one: $A^b_{FB}$)

=> Bulk flavor structure
<table>
<thead>
<tr>
<th><strong>5D holographic version</strong></th>
<th><strong>RS with bulk fields</strong></th>
<th><strong>gauge-Higgs unification</strong></th>
<th><strong>Higgsless models</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4D dual [in AdS/CFT] interpretation</strong></td>
<td><strong>composite Higgs boson</strong></td>
<td><strong>composite Higgs pseudo-Goldstone boson of a global symmetry (as for little Higgs with T parity)</strong></td>
<td><strong>technicolor models</strong></td>
</tr>
<tr>
<td><strong>EW constraints</strong></td>
<td><strong>S, T within 95% C.L. [S&gt;0 ; T&gt;0 ; U ≈ 0] for M_{KK} \approx 3\text{TeV}, m_h \approx 115-500 \text{ GeV}</strong></td>
<td><strong>S, T within 95% C.L. [S&gt;0 ; T&gt;0, &lt;0 ; U ≈ 0] for M_{KK} \approx 3\text{TeV}, m_h \approx 115-190 \text{ GeV}</strong></td>
<td><strong>S=1.15 (excess by factor 5) ; T ≈ 0 ; U ≈ 0, for M_{KK} \approx 1.2\text{TeV}</strong></td>
</tr>
</tbody>
</table>

(without custodial: e.g. M_{KK} \approx 6.4\text{TeV} , m_h \approx 1\text{TeV})
II) Comparison of EW fits in RS/SM

The RS model with bulk fields:

- RS addresses the gauge hierarchy:
  \[ M_{\text{grav}} \approx 1 \text{ TeV} \approx Q_{\text{EW}} \]

- RS generates the mass hierarchies:
  \[ m_e \ll m_t \]

Planck–brane  TeV–brane
Improved goodness-of-fit

EW observables are expressed in terms of oblique parameters encoding the New Physics...

\[
S_{RS} \simeq 2\pi \left( \frac{2.4v}{M_{KK}} \right)^2 \quad T_{RS} \simeq k^{\frac{2}{3}} R e \frac{\tilde{g}^2 \tilde{M}^2}{k^2} \left( \frac{2.4v}{M_{KK}} \right)^2
\]
Better quality of fit in RS than in SM cause..

1) positive contribution $T_{RS}$ *(custodial symmetry breaking)*

2) SM fit degraded by the $\sin^2 \theta_W$ measurement derived *directly* from $A_{FB}^{b}$:

\[
\begin{align*}
A_{fb}^{0,l} & = 0.23099 \pm 0.00053 \\
A_{l}(P_{\tau}) & = 0.23159 \pm 0.00041 \\
A_{l}(SLD) & = 0.23098 \pm 0.00026 \\
A_{fb}^{0,b} & = 0.23221 \pm 0.00029 \\
A_{fb}^{0,c} & = 0.23220 \pm 0.00081 \\
Q_{fb}^{had} & = 0.2324 \pm 0.0012 \\
\end{align*}
\]

Average

$0.23153 \pm 0.00016$

\(\chi^2/d.o.f.: 11.8/5\)
RS fit can be better for any $m_h > 115\text{GeV}$ (e.g. $m_h = 190\text{GeV} \Rightarrow h \to Z^0 Z^0$)

For $m_h = 500\text{ GeV}$

\[
\begin{cases}
\text{p-value can be @ 25.3\% in RS if } M_{KK} = 4\text{ TeV} \\
\text{p-value is only @ 2.5 \times 10^{-9} in SM} \\
\text{m}_h\text{ excluded in gauge-Higgs unification & SUSY}
\end{cases}
\]

=> the discovery of a heavy Higgs would constitute a sign for RS

The best-fit $m_h$ value is possibly larger than the LEP2 direct limit of 115GeV

*in contrast* with the SM where the best-fit $m_h$ is $76^{+24}_{-24} \text{ GeV}$ (getting even smaller by excluding $A^b_{FB}$)
III) The case of heavy flavors

\[ A^b_{FB} : \text{a NP effect in the b sector?} \]

\[ A^b_{FB}(\text{pole}) = \frac{\int_0^1 \sigma_\theta d\cos\theta - \int_{-1}^0 \sigma_\theta d\cos\theta}{\sigma_0(e^+e^- \rightarrow \gamma/Z \rightarrow b\bar{b})} \]

\[ = \frac{3 (Q^{eL}_{Z})^2 - (Q^{eR}_{Z})^2 - (Q^{bL}_{Z})^2 - (Q^{bR}_{Z})^2}{4 (Q^{eL}_{Z})^2 + (Q^{eR}_{Z})^2 (Q^{bL}_{Z})^2 + (Q^{bR}_{Z})^2} \]

\[ R_b = \frac{\Gamma(Z \rightarrow b\bar{b})}{\Gamma(Z \rightarrow \text{hadrons})} \]

\[ = \frac{(Q^{bL}_{Z})^2 + (Q^{bR}_{Z})^2}{\sum_{q \neq t} [(Q^{qL}_{Z})^2 + (Q^{qR}_{Z})^2]} \]
Interpretation in a generic extra-dimensional model:

\[
\left| \delta Q_Z^f \right| \approx 1\% \quad < \quad \left| \delta Q_Z^{b/L/R} \right| \approx -1.5/30\%
\]

Coupling \( Z_{KK} f \bar{f} \quad < \quad \) Coupling \( Z_{KK} b \bar{b} \)

\[ m_{b'}(c_{t_R}) \quad < \quad m_{f'}(c_{light}) \]

\[ m_t(c_{t_R}) \quad \uparrow \quad \Rightarrow \quad m_{b'}(c_{t_R}) \quad \downarrow \]

natural conditions within the RS model
Fit of $R_b + 8$ data for $A^b_{FB}(\sqrt{s})$
**Global $A_{FB}^b$ fit @ and off the Z pôle:**

\[ A_{FB}^b(s \sim M_Z^2) \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>24</td>
</tr>
<tr>
<td>RSa</td>
<td>20</td>
</tr>
<tr>
<td>RSb</td>
<td>14</td>
</tr>
</tbody>
</table>

\( b_R \) under \( SU(2)_L \times SU(2)_R \times U(1)_X \):

\[
\begin{align*}
Q_X &= (B - L)/2 \Rightarrow I_R^3 = -1/2 \quad \text{RSa} \\
Q_X &= -5/6 \Rightarrow I_R^3 = +1/2 \quad \text{RSb}
\end{align*}
\]
IV) Testing warped ED models at ILC

*Indirect* effects mainly in the heavy quark sector
(b,t couplings to KK bosons up to $\times \sqrt{2\pi kR_c} \approx 8$)

 маш Giga-Z: more data on $A^b_{FB} / R_b$ to confirm or invalidate the anomaly
(and its possible RS interpretation)

Contribution from s-channel exchange of KK Z, KK photon to top pair
production in $RS \rightarrow ILC$ sensitivity on $M_{KK}$ ($\delta \sigma \approx 1\%$, $A^t_{LR} \approx 0.002$):

$\sim 10-20$ TeV ! ...out of LHC reach {little hierarchy} 

[De Pree, Sher 06]
\[ e^+ e^- \rightarrow \gamma / Z^{(n)}_{KK} \rightarrow t\bar{t} \]

\[ M_{KK} = 3 \text{ TeV} \]
Through FCNC...

Tree-level FCNC process $e^+e^- \rightarrow t\bar{c}$ through $Z^0$-KK's mixing in RS:

$$\sigma_{tc} / \sigma_{\mu\mu} \approx 2 \times 10^{-5} \text{ at } \sqrt{s} \approx 200 \text{ GeV}$$

(+ angular distributions @ ILC can probe the prediction of Right-handed coupling dominance)

[Agashe, Perez, Soni 06]
Higgs compositeness effects / KK gauge boson mixings
⇒ $h^0$ vertex corrections
⇒ deviations in $\sigma(ff \rightarrow h^0) \times B(h^0 \rightarrow ...)$ [model-independent study]

[Giudice, Grojean, Pomarol, Rattazzi]

⇒ testable at LHC when deviations reach 20-60% ($m_h < 150$ GeV)
testable at ILC already @ the level of a few %

Gravity-induced EWSB scenario in URS:
⇒ corrections testable at ILC in $g_{h^0WW}^{SM}/g_{h^0WW} \approx 0.5 - 0.7$ ($m_h < 1$ TeV)

[Davoudiasl, Lillie, Rizzo 05]

precise $m_h$ reconstruct. @ILC VEV measurement ($h^0Z^0$ prod.)

$\lambda_h$ experimental estimation

⇒ to be compared with e.g. $\text{VEV}_{RS}$

Higgs-radion mixing effects ...
Possibly even \textit{direct} effects

\begin{itemize}
\item within composite pseudo-GB Higgs scenarios where $m_{\text{custodians}} \sim 500\text{GeV}$
\item $[\ll M_{\text{KK}} \sim 3\text{TeV}]$ can be compatible with precision EW constraints:
\item [Contino, Da Rold, Pomarol 06]
\item the \textit{single production} of these `custodians' (exotic colored fermions like $b'$, $q_{5/3}$ ...) becomes accessible by a 1TeV $e^+e^-$ machine..
\item KK Higgs excitation in \textit{URS}:
\item \textit{possible/difficult} in a 1TeV ILC ($\approx 10^{-1}$ reduced $h^{(1)}$-boson couplings)
\item [Davoudiasl, Lillie, Rizzo 05]
\end{itemize}
V) Conclusion

We have shown how, thanks to the custodial symmetry, flavor structure and quark representations, the \textit{RS} model can simultaneously:

- solve the forward-backward \textit{Anomaly} for the bottom
- improve the \textit{quality} of precision EW fits \textit{w.r.t. SM}
- for a best-fit Higgs mass above the \textit{LEP2 limit}.

\textit{There exist various precision tests of warped ED models at ILC, mostly in the third generation quark sector.}
& another model for $m_h = 500$ GeV ...