Higgs searches and Extra dimensions

QCD and High Energy Interactions

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The outline of this talk is:

- Introduction
- Extra dimensions and Composite Higgs
- Scalar Higgs
  - Randall-Sundrum (AdS)
  - Deformed metric
  - LHC limits
  - The radion
- Gauge-Higgs
- Conclusion
LHC is trying to answer the fundamental question

What is the nature of the electroweak symmetry breaking?

- Is it a perturbative mechanism [as the Brout-Englert-Higgs (BEH) one] or a non-perturbative one [as in QCD]?
- From the experimental point of view everything seems to be consistent with the SM with the BEH mechanism [aka Higgs mechanism] and possibly with a Higgs scalar around 124-126 GeV
- However from the theoretical point of view such electroweak vacuum is not stable under quantum corrections [aka hierarchy problem] and new physics should stabilize it

Uncovering the nature of electroweak breaking should amount to uncovering the kind of new physics (if any) which stabilizes the electroweak vacuum
There are two main avenues for solving the hierarchy problem

**Elementary Higgs**
- There should exist an **extra symmetry** and **new particles** with couplings dictated by this symmetry such that quadratic sensitivity to high scale cancels
- Typical example is **supersymmetry**: stops cancel the quadratic divergence generated by the top quark

**Composite Higgs**
- At some scale the Higgs **dissolves** and the theory of constituents is at work
- Similar to QCD where the pions dissolve into quarks
- The **compositeness scale** acts as a cutoff of quadratic divergences
- Typical example of compositeness is **technicolor**
- Modern theories of compositeness involve an **extra dimension** through the AdS/CFT correspondence

Guido’s talk
The original AdS/CFT correspondence relates 5D theories of gravity in AdS to 4D strongly-coupled conformal field theories. In the case of a slice of AdS a similar correspondence can also be formulated.

- Boundary at $y = 0$ corresponds to UV cutoff in the 4D CFT.
- $y = y_1$ corresponds to IR cutoff.
- Matter at UV is elementary: e.g. light fermions.
- Matter at IR is composite: e.g. KK modes, heavy fermions, ...

Although the CFT picture is useful for understanding some qualitative aspects of the theory it is useless for obtaining quantitative predictions since the theory is strongly coupled.
An AdS 5D theory with two branes was proposed long ago \(^1\). To solve the hierarchy problem the Higgs should be either:

- **Localized** on the IR brane (composite): theory is EWPT disfavored.
- **Propagating** in the bulk but with a profile along the extra dimensions tilted towards the IR brane (a degree of compositeness).

The hierarchy problem is solved because the Planckian Higgs mass is warped down to the weak scale by the geometry.

A Higgs propagating in the bulk can be

### Scalar-Higgs: \( H \)

*EWPT require either*

- An extra (custodial) gauge symmetry in the bulk: non-minimal models
- The AdS metric is deformed in the IR: minimal 5D SM

### Gauge-Higgs: \( A_5 \)

- The Higgs is part of an extended gauge group (which can contain a custodial symmetry)
- The Higgs bulk mass is protected by gauge inv

We will then consider the SM propagating in a 5D space with an arbitrary metric $A(y) \equiv A(ky)$: fundamental scale $k \simeq M_P$

$$ds^2 = e^{-2A(y)} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

A bulk Higgs field

$$H(x, y) = \frac{1}{\sqrt{2}} e^{i\chi(x, y)} \begin{pmatrix} 0 \\ h(y) + \xi(x, y) \end{pmatrix}, \quad h(y) = h(0) e^{aky}$$

The parameters of the effective Lagrangian for the Higgs boson,

$$\mathcal{L}_{\text{eff}} = -|D_{\nu} H|^2 + \mu^2 |H|^2 - \lambda |H|^4,$$

$$\lambda \sim Z^{-2}; \quad \rho = ke^{-A(y_1)}; \quad m_H^2 = \frac{2}{Z} \left( M_1/k - a \right) \rho^2$$

$$Z = k \int_0^{y_1} dy \frac{h^2(y)}{h^2(y_1)} e^{-2A(y)+2A(y_1)}$$
**AdS Metric**

- In the RS model the metric is conformally symmetric $A(y) = ky$
- $Z = O(1)$ and the natural value of the Higgs mass is TeV
- Confronting the model with EWPT implies heavy KK modes (unless extra custodial gauge) and a little fine-tuning problem

![Graph 1](#)

**For $m_H = 125$ GeV**

- No hope to detect KK modes at LHC
- Fine-tuning at few per mille
A possible solution to the previous problem is deforming the metric, as in soft-walls used in AdS/QCD theories

\[ A(y) = ky - \frac{1}{\nu^2} \log (1 - y/y_s) \]

AdS is \( \nu \to \infty \) and/or \( y_s \to \infty \)

AdS and deformed metric differ only in the IR region

- The warping more efficient in the deformed metric theory
- The compactification volume smaller in the deformed metric theory
- The parameter \( Z \gg 1 \) \( \Rightarrow \) lighter Higgs

The natural value of the Higgs mass is $O(10^2)$ GeV

Confronting the model with EWPT implies not so heavy KK modes and fine-tuning $\sim 10\%$

For $m_H = 125$ GeV

- KK modes at TeV can in principle be detected at LHC
- Fine-tuning $\sim 10\%$

(c) [(d)] is $\nu = 0.7$ [\nu = 0.6]
One can compute

\[ h^2_{WWH} = h^2_{WWH,SM} [1 - \xi], \quad \xi = O(m^2_H/m^2_{KK}) \simeq 0.01 \]

so a light Higgs unitarizes the theory in a similar way to the SM Higgs.

However extracting the signal at LHC will be challenging.\(^2\)

SM, dotted; the deformed model, solid; KK gluon exchange, dashed

LHC limits on graviton KK modes

The present CMS limits on graviton KK modes ($\tilde{k} = k/M_P$)

\[ \tilde{k} \leq 0.1 \]

CMS 2.2 fb$^{-1}$ at 7 TeV

$\Lambda_{\pi} > 10$ TeV

95% CL Exclusion

Electroweak 95% CL Exclusion

\[ M_1 [\text{GeV}] \]

\[ \text{Coupling } k \]

S. Chatrchyan et al. [CMS Collaboration], arXiv:1112.0688 [hep-ex]
The present ATLAS limits on graviton KK modes

The radion $F^{(0)}(x)$ is the quantum degree of freedom associated with fluctuations of the distance between the branes.

$$ds^2 = e^{-2A(y) - 2F(x,y)}[\eta_{\mu\nu} + h_{\mu\nu}(x, y)]dx^\mu dx^\nu + [1 + 2F(x, y)]dy^2$$

- It is the lightest non-SM state
- It can appear in the Higgs portal through the coupling

$$S = -\xi \int d^5x \sqrt{-g} \mathcal{R} \ H^\dagger H$$

- It mixes with the Higgs and can mimic/modify the Higgs phenomenology \(^5\) (very model and $\xi$ dependent)

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\(^5\) G. F. Giudice, R. Rattazzi and J. D. Wells, hep-ph/0002178
For a recent analysis in RS:

\[ m_h = 125 \text{ GeV} \]

\[ m_\phi = 137 \text{ GeV} \]

\[
\begin{align*}
R_h(\gamma\gamma) &\sim 1.3, \\
R_h(4\ell) &\sim 1.5, \\
R_\phi(\gamma\gamma) &\sim 1.3, \\
R_\phi(4\ell) &\sim 0.5
\end{align*}
\]

The gauge symmetry $G$ can protect the mass of extra dimensional components of gauge bosons.

$A^A_\mu$ ($A^A_5$) are gauge bosons (scalars) in four dimensions.

$G$ is broken by boundary conditions to $H_{UV}$ ($H_{IR}$) on the UV (IR) brane.

$$dS^2 = \frac{R^2}{z^2} (dx_4^2 - dz^2)$$
For $\mathcal{H}_{UV} = SU(2)_L \otimes U(1)_Y$ the number of PGB is $\text{dim}(G/H_{IR})$.

Different models differ so by $G$ and $H_{IR}$.

<table>
<thead>
<tr>
<th>Model</th>
<th># Goldstones ($A_5^3$)</th>
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<tbody>
<tr>
<td>$SO(4)/SO(3)$</td>
<td>$6-3=3$ (Higgsless SM)</td>
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<tr>
<td>$SU(3)/SU(2) \times U(1)$</td>
<td>$8-4=4$ ($H_{SM}$)</td>
</tr>
<tr>
<td>$SO(5)/SO(4)$</td>
<td>$10-6=4$ ($H_{SM}$)</td>
</tr>
<tr>
<td>$SO(6)/SO(5)$</td>
<td>$15-10=5$ ($H_{SM}$ + singlet)</td>
</tr>
<tr>
<td>$SO(6)/SO(4) \times SO(2)$</td>
<td>$15-6-1=8$ ($H_u, H_d$)</td>
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Some of the models contain the custodial group $SO(4)$ on the IR brane and so contribution to $T$ parameter protected.

In the dual theory $G/H_{IR}$ is characterized by the scale $f$.

The expansion parameter in the theory

$$\xi = \left(\frac{v}{f}\right)^2$$

$$h_{WWH}^2 = h_{WWH,SM}^2 [1 - \xi]$$

$\xi \to 0 \Rightarrow$ SM limit

$\xi \to 1 \Rightarrow$ Technicolor limit

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SU(2)_L \otimes U(1) breaking is radiative

One can consider an effective theory \(^a\) parametrized by \(\xi\) which measures the degree of compositeness of the Higgs

\(^a\) J. R. Espinosa, C. Grojean and M. Muhlleitner, arXiv:1003.3251 [hep-ph]
All Higgs couplings depart from the SM values by quantities proportional to $\xi$.

Unitarity must be restored by new (TeV) resonances at scales which depend on $\xi$.

Models have been confronted to EWPT and direct searches. 

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**Conclusion**

- The next step in Higgs search belongs to LHC
- If Higgs is confirmed at $m_H \simeq 125$ GeV and cross sections are consistent with SM expectations

**There should be no problem with**

- Perturbative unitarity
- (Meta)Stability

- If Higgs is confirmed at $m_H \simeq 125$ GeV and cross sections are not consistent with SM expectations then

**Other direct searches should uncover**

- Supersymmetry
- Composite Higgs
- Extra dimensions
- Unexpected new physics, ...