WARPED/COMPOSITE PHENOMENOLOGY SIMPLIFIED

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CERN - TH

THE CASE FOR A COMPOSITE HIGGS

\[ m_* \]

\[ : \]

\[ \{ \]}

a new strongly-interacting dynamics with heavy resonances is responsible for EWSB

\[ m_W \]

\[ \cdots \]}

\[ W_L, Z_L \] are Goldstone bosons of the new dynamics
THE CASE FOR A COMPOSITE HIGGS

a new strongly-interacting dynamics with heavy resonances is responsible for EWSB

composite Higgs

$W_L, Z_L$ are Goldstone bosons of the new dynamics
Can the composite Higgs be naturally light?
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$W^a_\mu, B_\mu$ 

$G \rightarrow \bar{G}$

$\begin{bmatrix}
\phi^0 \\
\phi^U, h
\end{bmatrix}$

enlarge the global symmetry to have a full SU(2) doublet

ex: $SO(5) \rightarrow SO(4)$
Can the composite Higgs be naturally light?

Yes, if it is a (pseudo) Goldstone boson

[Georgi & Kaplan, `80s]

The explicit breaking of the global symmetry by a weak interaction leads to a light Higgs

$$m_h^2 \sim \frac{\lambda^2}{16\pi^2} m_*^2$$

\[ W^a_{\mu}, B_\mu \]

\[ G \rightarrow \bar{G} \]

\[ \phi^\pm, \phi^0, h \]

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  The explicit breaking of the global symmetry by a weak interaction leads to a light Higgs

\[ m_h^2 \sim \frac{\lambda^2}{16\pi^2} m^2_* \]
A new fundamental parameter:

being a Goldstone, the composite Higgs behaves like an “angle”:

\[ V(h) = F_\pi^2 m^2 \frac{\lambda^2}{16\pi^2} g(h/F_\pi) \]

\[ F_\pi = \text{scale at which } G \rightarrow \tilde{G} \]
\[ g(x) = \text{periodic function} \]

new parameter:
\[ \epsilon = \frac{v}{F_\pi} \quad 0 \leq \epsilon \leq 1 \]
Composite Higgs from an extra warped dimension
Composite Higgs from an extra warped dimension

the Higgs structure along the extra dimension appears like a form factor for an observer on the UV brane
... ok, suppose we discover the Higgs: how can we tell it is composite?
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1. Measuring its couplings shifts expected at $\mathcal{O}(\epsilon^2)$
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1. Measuring its couplings
   
   shifts expected at $\mathcal{O}(\epsilon^2)$

2. Probing its strong interaction in the WW scattering
   
   the composite Higgs alone fails to fully unitarize WW scattering at high energy

$$\mathcal{A}(s, t) = \frac{s}{v^2} \epsilon^2 - \frac{s m_h^2}{s - m_h^2} (1 - \epsilon^2) + (s \leftrightarrow t)$$

see: Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706:045 (2007)
These signals would give **direct evidence** for the Higgs compositeness

- theoretically clean

- experimentally challenging

required: full control of the detector and of background
large integrated luminosity
Indirect evidence can come from the production of the new resonances of the strong sector

- experimentally easier
- more model dependent
Partners of the top
(resonances that cut off the loop of the top)

✔ Naturalness requires these new states to be light(er)

\[ m_h = 200 \text{ GeV} \]

ex:
\[ m_* \sim 700 \text{ GeV} \]

and NO tuning

✔ These states are colored fermions (no SUSY)

expected to be strongly coupled to t, b, W_L, Z_L

\[ h \]

\[ W, Z \]
Need a low-energy effective description of the lowest-lying resonances to study their phenomenology
we focus on the class of models with

- no T-parity

- linear couplings between composite and elementary sector
  - Flavor
  - Fermion masses

this includes extra-dimensional warped (Randall-Sundrum) theories
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effective description of the lowest-lying resonances given by a

Two-site model

R.C., Kramer, Son, Sundrum  JHEP 0705:074 (2007)
RULES

• Elementary sector:
  \[ \{ \text{SM - Higgs} \} \]
  inter-elementary coupling: \( g_{el} \sim 1 \)

• Composite sector:
  \[ \{ \rho, \chi + \text{Higgs} \} \]
  \[ \left[ \text{excited massive copy of the SM} \right] \]
  inter-composite coupling: \( 4 \pi \gg g_* \gg 1 \)

• Mixing:
  only mass mixings allowed

• Higgs:
  \( H \) couples only to \( \rho \) and \( \chi \)
\[ \mathcal{L}_{mix} = \sum_n \Delta_n \bar{\Psi} \chi_n + h.c. \]
elementary

\[ \psi \]

\[ \begin{array}{c}
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\end{array} \]

mass mixing

\[ \mathcal{L}_{\text{mix}} = \sum_n \Delta_n \bar{\psi} \chi_n + h.c. \]
elementary
\( \Psi \)

composites

\( \chi_n \)

\[ L_{mix} = \sum_n \Delta_n \bar{\Psi} \chi_n + h.c. \]
Keep only the first resonance of each tower

\[ \mathcal{L}_{mix} = \Delta \bar{\Psi} \chi + h.c. \]
example:

A simple Two-Site SO(5)/SO(4) model

\[ \text{SO}(5) \times \text{U}(1)_X \rightarrow \text{SO}(4) \times \text{U}(1)_X \]

\[ \Sigma_0 = (0, 0, 0, 0, 1) \]

\[ \text{SO}(4) \sim \text{SU}(2)_L \times \text{SU}(2)_R \]

\[ Y = T_{3R} + X \]
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4 Goldstones

\[ \Sigma = \Sigma_0 e^{T^a h^a} / F_\pi \]

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1 Heavy composite fermion multiplet

\[ 5_{2/3} \text{ of } \text{SO}(5) \times U(1)_X \]

\[ [5 = (2, 2) \oplus (1, 1)] \]
example: A simple Two-Site SO(5)/SO(4) model

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\text{SO}(5) \times U(1)_X \rightarrow \text{SO}(4) \times U(1)_X
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\]

\[
5 = (2, 2) \oplus (1, 1)
\]

\[
\chi = \begin{bmatrix}
(Q') \\
\tilde{T}
\end{bmatrix}
\]

\[
\begin{aligned}
q_L \\
t_R
\end{aligned}
\]
A simple Two-Site SO(5)/SO(4) model

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\[ \Sigma = \Sigma_0 e^{T^\alpha h^{\bar{\alpha}} / F_\pi} \]

\[ \chi = \begin{pmatrix} (Q') \\ \tilde{T} \end{pmatrix} \]

\[ q_L \]

\[ t_R \]

Composite sector
example: A simple Two-Site $\text{SO}(5)/\text{SO}(4)$ model

$\text{SO}(5) \times \text{U}(1)_X \rightarrow \text{SO}(4) \times \text{U}(1)_X$

$\Sigma_0 = (0, 0, 0, 0, 1)$

SO(4) $\sim$ SU(2)$_L \times$ SU(2)$_R$

$Y = T_{3R} + X$

4 Goldstones

1 Heavy composite fermion multiplet

$5_{2/3}$ of $\text{SO}(5) \times \text{U}(1)_X$

$[5 = (2, 2) \oplus (1, 1)]$

$\Sigma = \Sigma_0 e^{T^a h^a / F_\pi}$

$\chi = \begin{pmatrix} (Q') \\ \tilde{T} \end{pmatrix}$

$q_L$

t$_R$

elementary sector

composite sector
\[
\chi = \begin{pmatrix}
\left( \begin{array}{c}
Q' \\
Q \\
\tilde{T}
\end{array} \right)
\end{pmatrix}
\]

\[5 = (2, 2) \oplus (1, 1)\]

\[Q = \begin{pmatrix}
T \\
B
\end{pmatrix}
\]

\[Q' = \begin{pmatrix}
T_{5/3} \\
T_{2/3}
\end{pmatrix}
\]

\[Y[Q] = 1/6\]

\[Y[Q'] = 7/6\]
\[ \mathcal{L} = \bar{\chi} (i \partial - m) \chi - m \Sigma \bar{\chi}_i \Sigma_i \Sigma_j \chi_j \]
\[ + \bar{q}_L i \partial q_L + \bar{t}_R i \partial t_R \]
\[ + \Delta_q \bar{q}_L Q_R + \Delta_{t_R} \bar{t}_R \tilde{T}_L + h.c. \]
\[ \mathcal{L} = \bar{\chi} (i \slashed{\partial} - m) \chi - m \Sigma \bar{\chi}_i \Sigma_i \Sigma_j \chi_j \]

\[ + \bar{q}_L i \slashed{\partial} q_L + \bar{t}_R i \slashed{\partial} t_R \]

\[ + \Delta_q \bar{q}_L Q_R + \Delta_{t_R} \bar{t}_R \tilde{T}_L + h.c. \]

source of explicit SO(5) breaking
\[ \mathcal{L} = \bar{\chi} (i \partial - m) \chi - m \Sigma \bar{\chi} i \Sigma j \chi j \]

\[ + \bar{q}_L i \partial q_L + t_R i \partial t_R \]

\[ + \Delta q \bar{q}_L Q_R + \Delta t_R t_R \bar{T}_L + h.c. \]

\[ \mathcal{L} = + \bar{Q} \left( i \partial - m - m \Sigma \frac{s^2}{2} \hat{H} \hat{H}^\dagger \right) Q + \bar{Q}' \left( i \partial - m - m \Sigma \frac{s^2}{2} \hat{H}^c \hat{H}^{c \dagger} \right) Q' \]

\[ + \bar{T} \left( i \partial - \tilde{m} + m \Sigma s^2 \right) \tilde{T} - m \Sigma \frac{s^2}{2} \bar{Q}' \hat{H} \hat{H}^{c \dagger} Q + h.c. \]

\[ - m \Sigma \frac{sc}{\sqrt{2}} \left( \bar{Q} \hat{H}^c \tilde{T} + \bar{Q}' \hat{H} \tilde{T} + h.c. \right) \]

\[ + \bar{q}_L i \partial q_L + t_R i \partial t_R + \Delta q \bar{q}_L Q_R + \Delta t_R t_R \bar{T}_L + h.c. \]

\[ s \equiv \sin \frac{h}{F_\pi} , \quad c \equiv \cos \frac{h}{F_\pi} \]

\[ \hat{H} \equiv \frac{1}{\hbar} H = \frac{1}{\hbar} \left[ \frac{h^1 - ih^2}{h^3 - ih^4} \right] \quad h = \sqrt{\hbar \hat{a} \hbar \hat{a}} \]

\[ \tilde{m} = m + m \Sigma \]
Higgs potential

\[
\sin \frac{h}{F_\pi} \cos \frac{h}{F_\pi} \\
\tilde{T} \\
T \\
\tilde{T} \\
T \\
\tilde{T} \\
T \\
t_R \\
t_L \\
\sin \frac{h}{F_\pi} \cos \frac{h}{F_\pi}
\]
Higgs potential

\[ F(p^2) = y_t \cdot \frac{m\tilde{m} (p^2 + m\tilde{m})}{(p^2 - m^2)(p^2 - \tilde{m}^2)} \]
$F(p^2) = y_t \frac{m\tilde{m} \left(p^2 + m\tilde{m}\right)}{(p^2 - m^2)(p^2 - \tilde{m}^2)}$

$i \frac{1}{p^4 \Pi^q(p^2)}$

$\Pi^q(p^2) = \frac{1 + p^2 (m^2 + \Delta_q^2)^{-1}}{1 + p^2 m^{-2}}$
\[
F(p^2) = y_t \frac{m \tilde{m} (p^2 + m \tilde{m})}{(p^2 - m^2)(p^2 - \tilde{m}^2)}
\]

\[
\Delta V(h) = -\frac{2N_c}{8\pi^2} F_{\pi}^2 \int_0^\infty dp \frac{F^2(-p^2)}{\Pi_q(-p^2)\Pi_{t\pi}(-p^2)} \sin^2 \frac{h}{F_{\pi}} \cos^2 \frac{h}{F_{\pi}}
\]

\[
\approx -\frac{2N_c}{8\pi^2} y_t \frac{m^2}{6} F_{\pi}^2 \sin^2 \frac{h}{F_{\pi}} \cos^2 \frac{h}{F_{\pi}}
\]
Diagonalization: elementary/composite → light/heavy

\[
\begin{pmatrix}
q_L \\
Q_L
\end{pmatrix}
\rightarrow
\begin{pmatrix}
\cos \varphi_L & -\sin \varphi_L \\
\sin \varphi_L & \cos \varphi_L
\end{pmatrix}
\begin{pmatrix}
q_L \\
Q_L
\end{pmatrix}
\]

\[
\tan \varphi_L = \frac{\Delta q_L}{m}
\]

\[
\begin{pmatrix}
t_R \\
\tilde{T}_R
\end{pmatrix}
\rightarrow
\begin{pmatrix}
\cos \varphi_{tR} & -\sin \varphi_{tR} \\
\sin \varphi_{tR} & \cos \varphi_{tR}
\end{pmatrix}
\begin{pmatrix}
t_R \\
\tilde{T}_R
\end{pmatrix}
\]

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\tan \varphi_{tR} = \frac{\Delta t_R}{\tilde{m}}
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**Diagonalization:**  

Elementary/composite $\rightarrow$ light/heavy

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\begin{pmatrix}
t_R \\
\tilde{T}_R
\end{pmatrix}
\]

\[
\tan \varphi_{tR} = \frac{\Delta t_R}{\tilde{m}}
\]

\[
|SM\rangle = \cos \varphi \, |\Psi\rangle + \sin \varphi \, |\chi\rangle
\]

\[
|h\text{eavy}\rangle = -\sin \varphi \, |\Psi\rangle + \cos \varphi \, |\chi\rangle
\]
Diagonalization: \[\text{elementary/composite} \rightarrow \text{light/heavy}\]

\[
\begin{pmatrix}
q_L \\
Q_L
\end{pmatrix} \rightarrow 
\begin{pmatrix}
\cos \varphi_L & -\sin \varphi_L \\
\sin \varphi_L & \cos \varphi_L
\end{pmatrix}
\begin{pmatrix}
q_L \\
Q_L
\end{pmatrix}
\]

\[
\tan \varphi_L = \frac{\Delta q_L}{m}
\]

\[
\begin{pmatrix}
t_R \\
\tilde{T}_R
\end{pmatrix} \rightarrow 
\begin{pmatrix}
\cos \varphi_{tR} & -\sin \varphi_{tR} \\
\sin \varphi_{tR} & \cos \varphi_{tR}
\end{pmatrix}
\begin{pmatrix}
t_R \\
\tilde{T}_R
\end{pmatrix}
\]

\[
\tan \varphi_{tR} = \frac{\Delta t_R}{\tilde{m}}
\]

\[
|SM\rangle = \cos \varphi |\Psi\rangle + \sin \varphi |\chi\rangle
\]

\[
|\text{heavy}\rangle = -\sin \varphi |\Psi\rangle + \cos \varphi |\chi\rangle
\]

\[\varphi\ \text{parametrizes the degree of partial compositeness}\]
\[ \mathcal{L} = \bar{q}_L i \partial q_L + t_R i \partial t_R \]
\[ + \bar{Q} (i \partial - m_Q) Q + \bar{Q'} (i \partial - m) Q' + \bar{T} (i \partial - m_{\tilde{T}}) \tilde{T} \]
\[ - Y_* \left[ (\sin \varphi_L \bar{q}_L + \cos \varphi_L \bar{Q}) H^c (\sin \varphi_{t_R} t_R + \cos \varphi_{t_R} \tilde{T}) \right. \]
\[ \left. + \bar{Q'} H (\sin \varphi_{t_R} t_R + \cos \varphi_{t_R} \tilde{T}) + h.c. \right] + \ldots \]
\[ m_{\tilde{T}} = \sqrt{\tilde{m}^2 + \Delta_{t_R}^2} \]
\[ m_Q = \sqrt{m^2 + \Delta_{q_L}^2} \]
\[ \tilde{m} = m + m_{\Sigma} \]
\[ Y_* = \frac{m_{\Sigma}}{F_{\pi} \sqrt{2}} \]
\[ \mathcal{L} = \bar{q}_L i \partial q_L + \bar{t}_R i \partial t_R \]

\[ + \bar{Q} (i \partial - m_Q) Q + \bar{Q}' (i \partial - m) Q' + \bar{T} (i \partial - m_\tilde{T}) \tilde{T} \]

\[ - Y_\ast \left[ \left( \sin \varphi_L \bar{q}_L + \cos \varphi_L \bar{Q} \right) H^c \left( \sin \varphi_{t_R} t_R + \cos \varphi_{t_R} \tilde{T} \right) + \bar{Q}' H \left( \sin \varphi_{t_R} t_R + \cos \varphi_{t_R} \tilde{T} \right) + h.c. \right] + \ldots \]

\[
\begin{align*}
m_{\tilde{T}} &= \sqrt{\tilde{m}^2 + \Delta_{t_R}^2} \\
m_Q &= \sqrt{m^2 + \Delta_{q_L}^2} \\
\tilde{m} &= m + m_\Sigma \\
Y_\ast &= \frac{m_\Sigma}{F_\pi \sqrt{2}} 
\end{align*}
\]

induced Yukawa coupling

\[ y_t = Y_\ast \sin \varphi_L \sin \varphi_{t_R} \]
Heavy partners of the top charge

\[ T_{5/3} \quad + \quad \frac{5}{3} \]
\[ T_{2/3} \quad + \quad \frac{2}{3} \]
\[ T \quad + \quad \frac{2}{3} \]
\[ B \quad - \quad \frac{1}{3} \]
\[ \tilde{T} \quad + \quad \frac{2}{3} \]
Heavy partners of the top charge

\[
\begin{align*}
T_{5/3} & \quad + \frac{5}{3} \\
T_{2/3} & \quad + \frac{2}{3} \\
T & \quad + \frac{2}{3} \\
B & \quad - \frac{1}{3} \\
\tilde{T} & \quad + \frac{2}{3} \quad \text{partner of } t_R
\end{align*}
\]
Heavy partners of the top

\begin{align*}
T_{5/3} & \quad + \frac{5}{3} \\
T_{2/3} & \quad + \frac{2}{3} \\
T & \quad + \frac{2}{3} \\
B & \quad - \frac{1}{3} \\
\tilde{T} & \quad + \frac{2}{3}
\end{align*}

\{ \text{partners of } q_L \} \quad \text{partner of } t_R
Heavy partners of the top

\[
\begin{align*}
T_{5/3} & \quad + \frac{5}{3} \\
T_{2/3} & \quad + \frac{2}{3} \\
T & \quad + \frac{2}{3} \\
B & \quad - \frac{1}{3} \\
\tilde{T} & \quad + \frac{2}{3}
\end{align*}
\]

\[
\left\{ \begin{array}{c}
SU(2)_R \text{ partners of } q_L \\
\text{partners of } q_L \\
\text{partner of } t_R
\end{array} \right\}
\]
Heavy partners of the top

\[
\begin{align*}
T_{5/3} & \quad + \frac{5}{3} \\
T_{2/3} & \quad + \frac{2}{3} \\
T & \quad + \frac{2}{3} \\
B & \quad - \frac{1}{3} \\
\tilde{T} & \quad + \frac{2}{3}
\end{align*}
\]

- SU(2)_R partners of q_L
- partners of q_L
- partner of t_R

most studies focused on
PAIR PRODUCTION

\[ g_3 \]
PAIR PRODUCTION

any of $T, B, T_{5/3}, T_{2/3}, \tilde{T}$
$\lambda_{Q'} = Y_\star \sin \varphi_{t_R}$

$\lambda_Q = Y_\star \sin \varphi_{t_R} \cos \varphi_L$

$\lambda_{\tilde{T}} = Y_\star \sin \varphi_L \cos \varphi_{t_R}$
ex:

\[ W_L^+ \rightarrow b_L \rightarrow \tilde{T} \]
Discovering the exotic $T_{5/3}$

work in progress
with G. Servant
Discovering the exotic $T_{5/3}$

work in progress
with G. Servant
Discovering the exotic $T_{5/3}$

\[ T_{5/3} \to W^+ W^- \]

\[ \bar{T}_{5/3} \to W^- \]

\[ t_R \to W^+ \]

\[ \bar{t}_R \to W^- \]

\[ b \to \]

\[ \bar{b} \to \]

\[ l^+ l^+ + E_T \]

\[ j j j j \]

work in progress with G. Servant
Discovering the exotic $T_{5/3}$

work in progress with G. Servant

$T_{5/3}$ $\bar{T}_{5/3}$$\bar{t}_R t_R b$ $W^+$ $W^-$ $l^+ l^+ + E_T j j j j j$
Discovering the exotic $T_{5/3}$

work in progress
with G. Servant

Same-sign leptons

Invariant mass
Conclusions
Conclusions

 Discriminating between an elementary and a composite Higgs must be a goal of the LHC
Conclusions

- Discriminating between an elementary and a composite Higgs must be a goal of the LHC

- Direct evidence from shifts in the couplings of the Higgs and WW scattering → challenging
Conclusions

★ Discriminating between an elementary and a composite Higgs must be a goal of the LHC

★ Direct evidence from shifts in the couplings of the Higgs and WW scattering → challenging

★ Indirect evidence might come much earlier by producing the partners of the top