Twin Higgs
from
Left-Right Symmetry

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Outline

• Introduction: Little Hierarchy Problem
• Twin Mechanism
• Twin Higgs from Left-Right Symmetry
• Phenomenology
• Summary
Recipe

- SU(4) Global symmetry in Higgs potential
- $H = (H_A, H_B)$ transforms as a fundamental
- Twin symmetry $A \leftrightarrow B$
- $\langle H \rangle = (0, 0, 0, f)$ break $SU(4)$ to $SU(3) \Rightarrow 7$ Goldstone bosons
- Gauge $SU(2)_A \times SU(2)_B \subset SU(4)$
- Promote top Yukawa to preserve Twin symmetry
Left-Right Models

\[ SU(2)_A \times SU(2)_B \quad \sim \quad SU(2)_L \times SU(2)_R \]

\[ Twin \quad \sim \quad L - R \]

\[ SU(2)_L \oplus SU(2)_R \]

\[ Q_L \leftrightarrow Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \]

\[ Z_2 \]

\[ : \quad : \]

\[ H_L \quad H_R \]

\[ H \]

\[ SU(4) \]

[Chacko, HSG, Harnik hep-ph/0512088]
Higgs Sector

- Focus on effective theory below the scale $\Lambda \sim 4\pi f$
- $H$ is Non-linearly realized
- Transforms under SU(4) as a fundamental non-linear representation

\[
\begin{pmatrix}
H_L \\
H_R
\end{pmatrix} = H = fe^{i\pi f} \begin{pmatrix}
0 \\
0 \\
0 \\
1
\end{pmatrix} ; \pi = \begin{pmatrix}
0 & 0 & 0 & h_1 \\
0 & 0 & 0 & h_2 \\
0 & 0 & 0 & C \\
h_1^* & h_2^* & C^* & \phi
\end{pmatrix}
\]

- Potential of $\pi$ is zero at tree level
- EW symmetry breaking is induced dynamically —via SU(4) violating interactions
Gauge Sector

Gauge symmetry

\[ SU(2)_L \times SU(2)_R \times U(1)_{B-L} \]

\[ \langle H \rangle = f \]

\[ \Downarrow \]

\[ U(1)_Y \]

left-right symmetry \( \Rightarrow g_L = g_R = g_2 \)

Massive gauge bosons: \( W_H^\pm \) and \( Z_H \) with masses

\[ m_{Z_H}^2 \sim \frac{g_1^2 + g_2^2}{g_2^2} m_{W_H^\pm}^2 \]

\[ m_{W_H^\pm}^2 = \frac{1}{2} g_2^2 f^2 \cos^2 \frac{v}{f} \]

\( Z' \) searches \( \Rightarrow f \gtrsim 2 \text{ TeV} \)
Fermion Sector

Light fermion masses come from terms

\[
\frac{(\overline{Q}_R H_R)(H_L^\dagger Q_L)}{\Lambda} \quad \text{and} \quad \frac{(\overline{Q}_R H_R^\dagger)(H_L Q_L)}{\Lambda}
\]

for down and up type respectively. Too small for top quark introduce one vector-like pair of quarks \( T_L \) and \( T_R \). We can write

\[
y \overline{Q}_R H_R^\dagger T_L + y \overline{Q}_L H_L^\dagger T_R + MT_L T_R
\]

\[
m_T^2 \sim M^2 + y^2 f^2
\]

- Preserve L-R symmetry
- \( M \) can be arbitrarily small
Cancellations

To see explicitly how are the quadratic divergent $m^2$ of $h_L$ cancelled, go to the non-linear representation

\[
\begin{pmatrix}
    H_L \\
    H_R
\end{pmatrix}
= H \sim
\begin{pmatrix}
    i h_L \\
    0 \\
    f - \frac{1}{2} \frac{h_L^\dagger h_L}{f}
\end{pmatrix}
\]

for top sector

\[
\bar{Q}_L H_L t_R + \bar{Q}_R H_R T_L = i \bar{Q}_L h_L t_R - \frac{1}{2} \frac{h_L^\dagger h_L}{f} T_L T_R + f T_L T_R + \ldots.
\]
\[
\begin{pmatrix}
\begin{array}{c}
H_L \\
H_R
\end{array}
\end{pmatrix} = H \sim \begin{pmatrix}
\begin{array}{c}
\begin{array}{c}
ih_L \\
0
\end{array} \\
\begin{array}{c}
f - \frac{1}{2} \frac{h_L^\dagger h_L}{f}
\end{array}
\end{array}
\end{pmatrix}
\]
for the gauge sector

\[
|D_L H_L|^2 + |D_R H_R|^2 = h_L^\dagger A^\dagger A h_L - h_L^\dagger h_L (A^\dagger A)_{22}
\]
Figure 1: $A^a_{L\mu}$ and $A^a_{R\mu}$
**EW Symmetry Breaking**

The mass of the Higgs doublet get a one loop correction from the top sector

$$ m^2 = - \frac{3}{8\pi^2} y^2 f^2 \ln\left(\frac{\Lambda^2}{f^2}\right) $$ (1)

large $f$ required by $Z'$ searches reintroduced certain amount of fine tuning. To decouple this constraint from the tuning problem,

- Order an extra scalar $\hat{H}$
- Impose $\hat{H} \rightarrow -\hat{H}$ symmetry
  so $\hat{H}$ does not couple to fermions.
- Require $<\hat{H}> = \hat{f} >> f$
So Far ....

\[ m_{Z_H}^2 \sim \frac{g_1^2 + g_2^2}{2}(\hat{f}^2 + f^2) \]
\[ m_T^2 \sim M^2 + y^2 f^2 \]

and

\[ \Delta m^2 = -\frac{3}{8\pi^2 y^2 f^2} \ln \left( \frac{\Lambda^2}{f^2} \right) \]

\( f \) is now allowed to be \(< \text{TeV} \Rightarrow \) fine tuning is milder
Higgs Potential and Fine Tuning

– Higgs $m^2$ get a negative contribution from top loop
– Positive contribution from gauge loop
– Tuning these two terms to get correct EW symmetry breaking fix $\hat{f}$ with $f$
– Fine tuning is $\sim 11\%$ for $f=800$ GeV and $27\%$ for $f=500$ GeV with the best case scenario $\Lambda = 4\pi f$
**µ Terms**

– With 2 Higgs, Global symmetry is $U(4) \times U(4)$
– There are separate global $U(1)$ factors for $H$ and $\hat{H}$
– They are broken by $f$ and $\hat{f} \Rightarrow 2$ Goldstone bosons
– One is eaten by $Z_H$, The other left uneaten, it is the $\phi^0$
– This global $U(1)$ is exact $\Rightarrow \phi^0$ remain massless

Add a mass term

$$BH_R^\dagger \hat{H}_R + \mu^2 \hat{H}^\dagger_L \hat{H}_L$$

These are technically natural. $\hat{H}_L \rightarrow -\hat{H}_L \Rightarrow$ dark matter
Summary

new parameters: \( f, \hat{f}, y, M, \sqrt{B} \) and \( \mu \) (very few)

- \( \hat{f} \) is fixed by \( f \) to get \( m_W \)
- \( y \) is fixed by \( m_t \)
- \( M \) is arbitrary. It can even be zero
- Free parameters \( \mu \) and \( \sqrt{B} \)

new particles:

- \( W^\pm_H, Z_H \)
- \( T_H \)
- 14-6=8: \( h^0, \hat{h}_L, \phi^+_R \) and \( \phi^0_R \)
Generic Spectrum

- $Z_H$: $\sim \hat{f} \sim 2.5m_{t_H}$
- $W_H$: $\sim \hat{f} \sim 2m_{t_H}$
- $t_H$: $\sim f$
- $\hat{H}_L$, $\phi^\pm$, $h^0$: $\sim 0.4m_{t_H}$, $\sim 0.3m_{t_H}$, $\sim 170GeV$
- $\phi^0$: $2\sqrt{B}$
"Linearize" Non-Linear Representation

\[ H = i \frac{\sin \sqrt{\chi}}{\sqrt{\chi}} e^{i \phi} \begin{pmatrix} h_1 \\ h_2 \\ C \\ \phi - i f \sqrt{\chi} \cot \sqrt{\chi} \end{pmatrix} \]

\[ \phi \rightarrow \frac{\hat{f}}{\sqrt{2} F (\cos x + \frac{\sin x}{x})} \phi \]

\[ h_1 \rightarrow 0 \]

\[ h_2 \rightarrow \frac{v + h}{\sqrt{2}} - i \frac{x \hat{f}}{\sqrt{2} F (\cos x + \frac{\sin x}{x})} \phi \]

\[ C \rightarrow - \frac{x \hat{f}}{F \sin x} C \]
Conclusion

– Left-right model

* Both gauge and Yukawa couplings break SU(4) but preserve the $Z_2$ symmetry
* Predict :
  · Extra gauge bosons $W^\pm_H$ and $Z_H$ with mass few TeV
  · Extra top quarks of mass $\sim f$
  · Scalar fields $h_L, \hat{h}_L, \phi^\pm$ and $\phi^0$ which are relatively lighter
* Dark matter candidate
* Solve the fine tuning up to 10 TeV
* Very few parameters : $f, \hat{f}, M, \mu$ and $\sqrt{B}$
* Expect LHC to see these exotic particles and test the model