The Twin Higgs

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with
Zackaria Chacko and Hock-Seng Goh

hep-ph/0506256, 0512088
Outline

• Motivation – LHC, New Physic and the little hierarchy problem
• Illustration – a toy model
• A Realistic Model
• Some Phenomenology
• Discussion
LHC & Naturalness

• An argument I’ve heard somewhere:

LHC’s 1\textsuperscript{st} year will be exciting!

This is because naturalness tells us something must cancel the quadratic divergence from the top sector.

This new physics should be at a TeV, and is related to the top by some symmetry.

It carries color! LHC will see it!
LHC & Naturalness

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Not necessarily…
Invisible New Physics
Invisible New Physics

- In the Twin Higgs – All of the new physics added to the SM at the TeV may be invisible.
The Little Hierarchy Problem
A Mexican Hat

- Examine a complex scalar with a potential

\[ V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4 \]

\[ \langle \phi \rangle^2 = \frac{\mu^2}{2\lambda} \equiv v^2 \]

- The physics Higgs field has a mass

\[ m_h^2 = 2\mu^2 = 4\lambda v^2 \]
Fine Tuning

• The Higgs potential is sensitive to the UV

\[ \mu^2 = \mu_0^2 + c\Lambda^2 \]

F.T. \sim Sensitivity to UV \sim \frac{\Lambda^2}{v^2} \frac{\partial v^2}{\partial \Lambda^2}, \ldots

In our case

\[ F.T. \sim \frac{c}{2\lambda} \frac{\Lambda^2}{v^2} = 2c \frac{\Lambda^2}{m_h^2} \]
**Fine Tuning**

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\]

In our case

\[
\text{F.T.} \sim \frac{c}{2\lambda} \frac{\Lambda^2}{v^2} = 2c \frac{\Lambda^2}{m_h^2}
\]

- An anthropological statement about our field:
  Fine tuning is considered Bad
SM Divergences

\[
\begin{align*}
\text{Diagram 1:} & \quad \frac{3y_t^2}{8\pi^2} \Lambda^2 \\
\text{Diagram 2:} & \quad \frac{9g^2}{64\pi^2} \Lambda^2 \\
\text{Diagram 3:} & \quad \frac{3\lambda}{8\pi^2} \Lambda^2
\end{align*}
\]
SM Divergences

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\end{align*}

F.T. = \frac{3y_t^2}{4\pi^2} \frac{\Lambda^2}{m_h^2}

\begin{align*}
\text{Diagram 2:} & \quad \frac{9g^2}{32\pi^2} \frac{\Lambda^2}{m_h^2} \\
\text{Diagram 3:} & \quad \frac{3}{16\pi^2} \frac{\Lambda^2}{v^2} \\
\end{align*}
SM Divergences

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Low cutoff or Heavy Higgs

Low cutoff
Fine Tuning in SM

• For $\Lambda = 5$ TeV and $m_h = 120 - 200$ GeV:

- $F.T. = \frac{3y_t^2}{4\pi^2} \frac{\Lambda^2}{m_h^2}$
  $\sim 0.75\% - 2\%$

- $F.T. = \frac{9g^2}{32\pi^2} \frac{\Lambda^2}{m_h^2}$
  $\sim 5\% - 13\%$

- $F.T. = \frac{3}{16\pi^2} \frac{\Lambda^2}{v^2}$
  $\sim 6\%$
EW data highly favors a light SM Higgs
### Precision EW II

<table>
<thead>
<tr>
<th>Dimensions six operators</th>
<th>$m_h = 115$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}<em>{WB} = (H^\dagger \tau^a H) W^{a}</em>{\mu \nu} B_{\mu \nu}$</td>
<td>$c_i = -1$</td>
</tr>
<tr>
<td>$\mathcal{O}_H =</td>
<td>H^\dagger D_\mu H</td>
</tr>
<tr>
<td>$\mathcal{O}<em>{LL} = \frac{1}{2}(\bar{L} \gamma</em>\mu \tau^a L)^2$</td>
<td></td>
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<tr>
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<tr>
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<td>$10$</td>
</tr>
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<td>$\mathcal{O}<em>{HL} = i(H^\dagger D</em>\mu H)(\bar{L} \gamma_\mu L)$</td>
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<tr>
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</tr>
<tr>
<td>$\mathcal{O}<em>{HU} = i(H^\dagger D</em>\mu H)(\bar{U} \gamma_\mu U)$</td>
<td>$6.1$</td>
</tr>
<tr>
<td>$\mathcal{O}<em>{HD} = i(H^\dagger D</em>\mu H)(\bar{D} \gamma_\mu D)$</td>
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Barbieri, Strumia
hep-ph/0007265
The EW scale should be stabilized compared to a cutoff of at least 5 TeV.
**LEP Paradox**

- The Little Hierarchy problem is the parametric tension between **Data** and **Naturalness**

- In the SM this is a tuning of order 1%.

However, if its take seriously, it may be a hint for what new physics is at a TeV.
Singlet NP

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<td>$\mathcal{O}_H$</td>
<td>$</td>
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<td>9.2</td>
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<td>2.5</td>
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$\Lambda \geq 5 \text{ TeV}$

Barbieri, Strumia
hep-ph/0007265
This motivates a scenario where all TeV new physics is a singlet under the SM.
Higgs as a PNGB

• If the Higgs is a Goldstone, its mass is insensitive to the cutoff due to symmetry.  
  May reduce fine tuning.

• May serve as an explanation for a light Higgs and a low EW scale (compared to 5 TeV)

• Old idea: Kaplan-Georgi  
  Revived with Little Higgs.

We propose an alternative realization.
A Toy Model
Global SU(4)

- Take a scalar field $H$, a fundamental under a global SU(4).
- Write a potential:

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

$$|\langle H \rangle|^2 = \frac{m^2}{2\lambda} \equiv f^2$$

SU(4) $\rightarrow$ SU(3)  $\Longrightarrow$  7 Goldstones
Gauge $\text{SU}(2)_A \times \text{SU}(2)_B$

- Now we gauge an $\text{SU}(2)_A \times \text{SU}(2)_B$ subgroup eventually –
  
<table>
<thead>
<tr>
<th>SM</th>
<th>“Twin” SM</th>
</tr>
</thead>
</table>

- The field $H$ transforms as

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$
Radiative Corrections

• Quadratic terms are generated:

\[ \Delta V(H) = \]
Radiative Corrections

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\[ \Delta V(H) = \frac{9g_A^2 \Lambda^2}{64\pi^2} H_A^\dagger H_A \]
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- Impose a “Twin” \( Z_2 \): \( A \leftrightarrow B \) \( g_A = g_B \)
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• Impose a “Twin” \( Z_2 \): \( A \leftrightarrow B \) \( \Rightarrow g_A = g_B \)

\[ \Delta V = \frac{9g^2 \Lambda^2}{64\pi^2} (H_A^\dagger H_A + H_B^\dagger H_B) \]

SU(4) invariant! Does not give a Goldstone mass!
The Twin Mechanism

• Due to a **discrete** symmetry the quadratic terms in the potential respect a **continuous global** symmetry that is otherwise broken.

• Higher order terms are not SU(4) invariant.

\[ \Delta V = \kappa (|H_A|^4 + |H_B|^4) \]

with \[ \kappa \sim \frac{g^4}{16\pi^2} \log \frac{\Lambda^2}{f^2} \]

See Barbieri et al. For the $\kappa \sim 1$ option. hep-ph/0509242
Symmetric Vacuum

• The potential to minimize is

\[ V = -m^2|H|^2 + \lambda |H|^4 + \kappa (|H_A|^4 + |H_B|^4) \]

\[ \Rightarrow |\langle H_A \rangle|^2 = |\langle H_B \rangle|^2 = \frac{f^2}{2} \sim \frac{m^2}{4\lambda} \]

The pseudo-Goldstone mass is

\[ m_h \sim \sqrt{\kappa} f \sim \frac{g^2 f}{4\pi} \]

\[ \Rightarrow f \sim 1 \text{ TeV} \quad \text{for} \quad m_h \sim (\text{EW scale}) \]
Asymmetric Vacuum

• However, when $f_A^2 = \frac{f^2}{2} = (174 \text{GeV})^2$ and by NDA $\Lambda$ is at most $4\pi f$, the cutoff is below 5 TeV.

Nonetheless, Barbieri et al. analyze this case.
Asymmetric Vacuum

However, when \( f_A^2 = \frac{f^2}{2} = (174 \text{GeV})^2 \) and by NDA \( \Lambda \) is at most \( 4\pi f \), the cutoff is below \( 5 \text{ TeV} \).

Nonetheless, Barbieri et al. analyze this case.

But if \( f_A < f_B \) we can get \( f_A << \Lambda \).
Asymmetric twins:
Soft $Z_2$ Breaking

- Add

$$V_{\text{soft}}(H) = \mu^2 H_A^+ H_A$$

a soft breaking of $Z_2$

$\Rightarrow$ does not introduce quadratic divergences.

$\mu$ is the only $Z_2$ breaking parameter.

$\mu \ll \Lambda$ is technically natural.

$\mu$ will be of order EW scale


Fine Tuning

- Minimizing the full potential

\[ f_A^2 = \frac{f^2}{2} - \frac{\mu^2}{4\kappa} \quad \text{with} \quad f^2 \sim \frac{m^2}{2\lambda} \]

- An estimate of the fine tuning-

\[ \text{F.T.} = \frac{f^2}{v^2} \frac{\partial v^2}{\partial f^2} = \frac{f^2}{2v^2} \]

F.T. \sim 25\% - 10\%
for
f \sim 500 - 800 \text{ GeV.}

The Higgs mass dependence is removed.
Eases tension b/w naturalness and data.
A Model
What Do We Need?

• Embed the top sector.
• Construct an EFT that realizes the symmetry.
• Set the cutoff (above 5 TeV).
• Verify that correct EWSB is achievable, and that the Higgs mass is within the bounds.
• Phenomenology, cosmology, etc.
\( \text{SM}_A \times \text{SM}_B \)

- We can utilize the Twin mechanism for all of the SM interactions:
  
  Take two SM's \( \text{SM}_A \times \text{SM}_B \times \mathbb{Z}_2 \)

- All of the radiative corrections to the Higgs mass, including those from the top, will respect the \( \mathbb{Z}_2 \) and SU(4).
Top

• The top sector then looks like

\[ \mathcal{L} = y_t H_A q_L^A t_R^A + y_t H_B q_L^B t_R^B + \text{h.c} \]

\[ \kappa \sim \frac{y_t^4}{16\pi^2} \log \frac{\Lambda^2}{f^2} \]

(with the right sign)

EWSB is triggered by the top (as usual).
Extended Top Sector

• We can remove the cutoff sensitivity from the top sector by breaking SU(4) softly –

\[
\begin{aligned}
\text{under} & \quad SU(6) \supset SU(3)_A \times SU(3)_B \\
& \quad SU(4) \supset SU(2)_A \times SU(2)_B
\end{aligned}
\]

introduce

\[
H = (1, 4) \quad Q = (6, 4) \quad T = (6, 1)
\]

and write

\[
\mathcal{L} \supset y HQT + \text{h.c.}
\]

Finally, we give a mass to the exotic tops, breaking SU(4) softly.
Effective Theory

• The most general way to stabilize the weak scale with the twin mechanism is to realize the symmetries in a non-linear sigma model.

• The d.o.f. in this model may be parameterized by

\[ H = e^{i \frac{T^a h^a}{f}} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \]

This is an effective theory of goldstones.

The cutoff \( \Lambda \) is at most \( 4\pi f \) by NDA.
Many UV Completions?

• The linear model is just an example of a UV completion to the non linear one –
  Lower the cutoff of the linear model to $\Lambda \sim m$ we are left with an EFT with just the goldstones.
  The NDA bound is saturated when the linear model is strongly coupled, $\lambda \sim (4\pi)^2$.

• We may well imagine other possible UV completions-
  Strong dynamics, SUSY, Turtles,…. 
Numbers

- In hep-ph/0506256 we analyzed the parameter space of the non-linear model for strong coupling.

<table>
<thead>
<tr>
<th>$\Lambda$ (TeV)</th>
<th>$f$ (GeV)</th>
<th>$M$ (TeV)</th>
<th>$M_B$ (TeV)</th>
<th>$\mu$ (GeV)</th>
<th>$m_h$ (GeV)</th>
<th>Tuning</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>800</td>
<td>6</td>
<td>1</td>
<td>239</td>
<td>122</td>
<td>0.134</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>5.5</td>
<td>1</td>
<td>145</td>
<td>121</td>
<td>0.378</td>
</tr>
<tr>
<td>10</td>
<td>800</td>
<td>—</td>
<td>0</td>
<td>355</td>
<td>166</td>
<td>0.112</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>—</td>
<td>0</td>
<td>203</td>
<td>153</td>
<td>0.307</td>
</tr>
</tbody>
</table>
An aside: Left-Right

• The same mechanism may be embedded in an $\text{SU}(2)_L \times \text{SU}(2)_R$ model with

\[ H = \begin{pmatrix} H_L \\ H_R \end{pmatrix} \]

• This model is much more visible-
  – Only one color group
  – Heavy tops
  – Heavy $\text{SU}(2)_R$ and $B-L$ gauge bosons
Phenomenology
Twin Photon

• We have introduced a whole twin SM. 

$\gamma_B$ – a twin photon!

potentially dangerous:

– Kinetic mixing can induce mili-charges for twin fermions.

• However,

Kinetic mixing is not induced upto 3 loops!

(Fine print: If we choose not to extend the top sector)
Twin Photon II

But-

• If we do extend the top sector, kinetic mixing is induced at one loop.

in this case we give $\gamma_B$ a mass
Cosmology

- The twin sector can have a wide variety of stable particles, e.g. twin neutrons DM candidates

- SM and twin sectors are in thermal eq. down to $T_d \sim 1\text{--}10 \text{ GeV}$

We must rid of the relativistic twin d.o.f. before BBN.
Cosmology II

• We can change the relative temperature of the two sectors after $T_d$:

1) Raise all twin fermion masses above $T_d$ – annihilations of SM fermions increase $T_{SM}$. (Barbieri et al)

2) Hope for more SM entropy production in the QCD phase transitions.

• Both of these require breaking the $Z_2$ for the small yukawas. (technically natural)
LHC Phenomenology

- A standard model Higgs.
LHC Phenomenology

• A standard model Higgs.

• But perhaps there is some hope-
  • LHC can see invisible decays of the higgs down to a BR of $\sim 15\%$.
  • $WW$ scattering becoming strong?....

• (in progress)
ILC

• The ILC can distinguish this model from the SM:

1) Small modifications, $O(v/f)$, to SM values of $ZZh$, $ZZhh$, $tth$, $hhh$, ...

2) Higgs decays to twin fermions with $BR \sim (v^2/f^2)$.

• All of these modifications are governed by one parameter, $v/f$. (in the full $Z_2$ limit).

• Non-trivial correlations b/w observables can be a smoking gun for this model (in progress).
Discussion
Summary

- The twin Higgs –
  A new realization of the Higgs as a PNGB.

- The mechanism –
  Due to a discrete symmetry, the quadratic divergences to the Higgs mass respect a global symmetry `accidentally`.

- Natural EWSB may be achieved, stabilizing the weak scale up to 5-10 TeV.
Twin vs. Little

• What’s the difference b/w twin and Little Higgs?

• EW precision has often forced LH to break the symmetry at a higher scale, typically $f \sim 1-2$ TeV (unless T-parity is added).

• A higher $f$ comes with additional fine tuning. (recall, in our case $F.T. \sim f^2/2v^2$).

• In the Twin Higgs $f$ can be smaller because all new physics is not charged under the SM.
LHC & Naturalness

- Naturalness does not imply that new physics is easily accessible at LHC.

We won’t have to give up naturalness if LHC does not see NP immediately.

Instead, we’d have to work hard to distinguish a natural model from an anthropic SM.
Extra slides
Left-Right

• The same mechanism may be embedded in an $SU(2)_L \times SU(2)_R$ model with

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• This model is much more visible-
  – Only one color group
  – Heavy tops
  – Heavy $SU(2)_R$ and $B-L$ gauge bosons
LHC Phenomenology

• A standard model Higgs.
• Some hope: …
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• All of these modifications are governed by one parameter, \(v/f\). (in the full \(Z_2\) limit).
• Non-trivial correlations b/w observables can be a smoking gun for this model (in progress).
The Cutoff

• Where is the cutoff?

$m^2$ is cutoff sensitive.

- Come up with a mechanism to stabilize $m^2$.
- Consider the effective theory below $m^2$. 
The Cutoff

- Where is the cutoff?

\( m^2 \) is cutoff sensitive.

Come up with a mechanism to stabilize \( m^2 \).

Consider the effective theory below \( m^2 \).

\[ \Lambda \sim m \]

- We integrate out the radial mode and are left with an effective theory of goldstones.
Low Cutoff

• Recall:  
  - In this toy model f is set buy m.
  - m is cutoff sensitive.

Naturalness requires that $\Lambda$ is not much above f.

• If

$$f_A^2 = \frac{f^2}{2} = 174\text{GeV}$$

\[ \text{cutoff is too low for precision EW} \]
Low Cutoff

• Recall:  
  - In this toy model f is set by m.
  - m is cutoff sensitive.

Naturalness requires that $\Lambda$ is not much above f.

• If
  
  \[ f_A^2 = \frac{f^2}{2} = 174\text{GeV} \]

  cutoff is too low for precision EW

• But if \( f_A < f_B \) we can get \( f_A \ll \Lambda \)
Linear Model

\[
\sqrt{2m} \quad \text{-- radial mode}
\]
Discussion

• The discussion will include a few slides about:
  – Comparison with little higgs. We can afford a low f.
  – The fact that we are refuting the lore that there needs to be new physics charged under the SM. And the lore that naturalness implies the LHC will see new colored states.
  – A summary of the mechanism and how it works.
  – Should I go into outlook and work that is in progress? (probably not, what do you think?)