Model Agnostic limits on Colored Top Partners

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Arxiv:1606(±1).xxxx
with Rouven Essig, Patrick Meade and Yiming Zhong
Talk Outline

- The Hierarchy Problem and colored top partners
- Effects on Higgs Precision Measurements
- Ways to Hide
- Results
The Hierarchy Problem

- Electroweak scale unnatural
- Require symmetries to protect a light Higgs mass
- Dire need for new physics
How Dire?

\[
\begin{align*}
&\text{top loop} & - \frac{3}{8\pi^2} \lambda_t^2 \Lambda^2 \\
&SU(2) \text{ gauge boson loops} & \frac{9}{64\pi^2} g^2 \Lambda^2 \\
&\text{Higgs loop} & \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \\
\end{align*}
\]

\[\Lambda_{\text{top}} \lesssim 2 \text{ TeV} \quad \Lambda_{\text{gauge}} \lesssim 5 \text{ TeV} \quad \Lambda_{\text{Higgs}} \lesssim 10 \text{ TeV}.
\]

Figures and numbers borrowed from Schmaltz and Tucker-Smith
Solutions
Colored Top Partners

- Supersymmetry $\Rightarrow \lambda_S = |\lambda_f|^2$

\[
V_{CW} \supset \sum_i (-1)^F \frac{1}{32\pi^2} M_i^2 \Lambda^2
\]

- Fermionic Top Partners

- Higgs is a PNGB

- In terms of Higgs couplings

\[
M_T \lambda_T = f \lambda_t^2
\]
Where are the colored TPs?

- Higher Mass of top partners => a more finely tuned theory (BAD)

- LEP+Tevatron+Run 1 see no stops/heavy tops (BAD)
Ways to test colored TP

- Copiously produced at the LHC
- Direct detection: decay to SM colored and LSP
- DD Caveats: Stealth SUSY, Oddest Little Higgs
- Same topologies definitely contribute to ggF and diphoton decay
- affect Higgs precision measurements.
To see what couplings for the Higgs arise we substitute the parameters from the top loop so we identify Eq. (37) and expand in powers of Yukawa couplings. For simplicity, let us also set $\lambda_2 = \pi$ and $\lambda = \sqrt{2}$, but the main points here are independent of this choice. We preserve two terms that both look like they contribute to the top Yukawa coupling, and the two cut-off terms that both look like they contribute to the top Yukawa coupling. For example, let us also set $f_t^2 = f_h^2 = 1$. The two cut-off terms cancel the quadratic divergence $f_t^2 f_h^2$ and $f_t^2 f_h^2$ by loops. The two cut-off terms are identical, so we identify

$$f_t^2 f_h^2 \sim 16 \left( t + \lambda \right) + \left( t^c + \lambda \right) t_t^2 t_h^2.$$
The quadratically divergent contribution to the Higgs mass is canceled by the loop.

Figure 5: The Dirac fermion yuk (41) symmetries. This is analogous to the situation in SUSY where the fermion yuk (42) preserves the two Higgs fields with coupling constant λh. The two terms that both look like they contribute to the top Yukawa coupling, and the mass, are of the form λh. For simplicity, let us also set λ = 2π.

In order for the two cut-off divergences to be forbidden by global symmetries and are therefore not generated from the top quark, we compute the fermion loops including interactions to the Higgs.

Top loop is canceled by the loop. The two Higgs fields with coupling constant λh cancel the quadratic divergence from the top loop.

The boson-fermion cancellation also relies on a supersymmetric regulator/cut-off mechanism and call them two terms that both look like they contribute to the top Yukawa coupling, and the mass, are of the form λh. For simplicity, let us also set λ = 2π.

In order for the two cut-off divergences to be forbidden by global symmetries and are therefore not generated from the top quark, we compute the fermion loops including interactions to the Higgs. The last term of the second line in Eq. (42) is the top Yukawa coupling, λt/√Λ. This will reduce the number of terms we encounter because it preserves the two Higgs fields with coupling constant λh. The two terms that both look like they contribute to the top Yukawa coupling, and the mass, are of the form λh. For simplicity, let us also set λ = 2π.

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Is it possible to kill the possibility of colored top partners ameliorating the hierarchy problem just from this property?

Or can we hide them by messing with other standard model yukawas?
Higgs Precision

- Production
  - ggF
  - VBF
  - WH
  - ZH
  - tth

- Decay
  - AA
  - WW,ZZ
  - bb
  - gg
  - invisible
Signal strength Modifiers

\[ r_f = \frac{\mu_f}{\mu_{fSM}} \]
Higgs Precision

- Production
  - $ggF$
  - $VBF$
  - $WH$
  - $ZH$
  - $tth$

- Decay
  - $AA$
  - $WW,ZZ$
  - $bb$
  - $gg$
  - invisible
Higgs Precision

- Production
  - $ggF$ \( rt(1+rtG) \)
  - VBF
  - WH
  - ZH
  - $tth$ \( rt \)

- Decay
  - $AA$
  - $WW,ZZ$
  - $bb$
  - $gg$ \( rt(1+rtG) \)
  - invisible
## Higgs Precision

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
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<tbody>
<tr>
<td>$ggF$</td>
<td>$AA$</td>
</tr>
<tr>
<td>$rt(1+rtG)$</td>
<td>$rV+rX-0.28rt(1+rtG)$</td>
</tr>
<tr>
<td>$VBF$</td>
<td>$WW,ZZ$</td>
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<td>$rV$</td>
<td>$rV$</td>
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<td>$WH$</td>
<td>$bb$</td>
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<td>invisible</td>
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<tr>
<td>$rt$</td>
<td>$rinv$</td>
</tr>
</tbody>
</table>
Data

- Full Run I
- Run II updated to Moriond
- Future colliders
SUSY

- Model agnostic conversion of rtG limits to stop masses  
  Refer Arxiv:1401.7671 Jiji Fan, Matt Reece

- Constrained rtG => smaller stop masses disallowed=>Tuned theory
Scalar: parameter potency

![Graphs showing various combinations of scalar parameters against (r'_G) fit,max](image)
Scalar parameter potency

$\tilde{r}_G + r_t$
$\tilde{r}_G + r_b$
$\tilde{r}_G + r_{\text{inv}}$
$\tilde{r}_G + r_V$
$\tilde{r}_G + r_{\tau}$
$\tilde{r}_G + r_{\chi_{\pm}}$
$\tilde{r}_G$ only

$(r_G^t)^{\text{fit;max}}$
CONCRETE REALIZATION
Extending the Higgs Sector

- 2HDM (refer to comprehensive Plenary talk by Carlos Wagner)
- Type-2 used in the MSSM
- Hu and Hd mix and share Higgs vev=246

\[ r_t = \sqrt{1 - \frac{r_b^2 - 1}{\tan^2 \beta}}, \quad r_V = \frac{\tan \beta}{1 + \tan^2 \beta} \left( \frac{r_b}{\tan \beta} + \sqrt{1 + \tan^2 \beta - r_b^2} \right). \]
Scalar: Concrete realization

\[ r_{G}^t + r_t \]
\[ r_{G}^t + r_b \]
\[ \tan \beta = 0.66 \]
\[ \tan \beta = 0.8 \]
\[ \tan \beta = 2.2 \]
\[ \tan \beta = 10 \]

4HDM
farewell
perturbativity

3 ab\(^{-1}\)
LHC Run 4
MSSM
Tuning

\[ \tan \beta = 0.66 \]

FCC-ee, CEPC, ILC, HL-LHC

\[ \Delta h = 3\% \]
\[ \Delta h = 3.5\% \]
\[ \Delta h = 7\% \]
\[ \Delta h = 15\% \]

\[ r_G^t \]

MSSM

\[ m_{\tilde{t}_1}, [\text{GeV}] \]
\[ m_{\tilde{t}_2}, [\text{GeV}] \]
Assume a singlet fermion with non-renormalizable coupling to the Higgs

\[(mT-a h^2)TTc\]

Cancellation condition \(\Rightarrow y_T = \frac{-m_t^2}{m_T^2}\)

We find even in the most general case with off-diagonal mixing, this elegant relation still holds.

\[rtG=yT\] a negative definite quantity for Little Higgs theories

Refer Arxiv:arXiv:1205.0013 Berger, Hubitz, Perelstein
Hiding Potency
Fermion: Concrete Realization

\[
\begin{align*}
\{y_T, y_t\} & \\
type-II, \tan \beta = 0.5 & \\
type-II, \tan \beta = 1 & \\
type-II, \tan \beta = 10 & \\
\{y_T, y_b\} &
\end{align*}
\]

\[m_T \text{ [GeV]}\]

3 ab\(^{-1}\)
LHC Run 4

Current Data

Idealized Current Data
Future Colliders

\[ \Delta h = 5\% \]

\[ \Delta h = 8\% \]

\[ \Delta h = 15\% \]

\[ \Delta h = 30\% \]

\[ \Delta h = 40\% \]

\( \{y_T, y_t\} \)

FCC–ee

CEPC

ILC

HL–LHC
- Vanilla SUSY $\Rightarrow$ fixes # stops
- Global symmetry like Little Higgs theories $\Rightarrow$ more top partners allowed.
- Extend with 1 more top partner
Two Fermionic top partners

\[ m_{T_1}[\text{GeV}] \]

\[ m_{T_2}[\text{GeV}] \]

\[ \Delta h = 0 \]
\[ \Delta h = 5\% \]
\[ \Delta h = 10\% \]
\[ \Delta h = 20\% \]

Fcc–ee
CEPC
ILC
HL–LHC (3ab\(^{-1}\))
Run 2 (300fb\(^{-1}\))
current
I thought he was at a stoplight... were is the red reflection on the windsheild/car

ill show a close up of his face ---->

How u drivin without keys!!! –––

Look at the date -------> 9 8 96
Summary

- Colored top partners hurtling towards demise
- Alternatives exist:
  A. Neutral Naturalness
  B. Relaxions, N-Naturalness
What is dead may never die