Recent Progress in Neutral Naturalness

Nathaniel Craig
UC Santa Barbara

CERN TH Institute: Charting the Unknown
\textbf{BS} = \text{constant} \\
\text{Strangeness} \\
(\text{Tuning})
Symmetry Solutions

Extend the SM with a symmetry acting on the Higgs

Supersymmetry

\[ \{ \text{Supersymmetry} \} \approx \frac{4\pi}{G} \]

\[ \text{Sparticles} \tilde{m} \]

\[ \text{Higgs} m_h \]

Global symmetry

\[ \{ \text{Global-symmetry} \} \approx \frac{4\pi}{G} \]

\[ \text{Partner particles} \tilde{m} \]

\[ \text{Higgs} m_h \]
Discrete symmetries

Symmetry-based approaches to hierarchy problem employ *continuous symmetries*. Leads to partner states w/ SM quantum numbers.

Discrete symmetries can also serve to protect the Higgs. Leads to partner states w/ non-SM quantum numbers.

“Neutral naturalness”
“Is neutral naturalness the beautiful reason we haven’t seen anything, or the last desperate hope of theorists?”

—G. Giudice
Progress in NN

[Chacko, Goh, Harnik '05; Barbieri, Gregoire, Hall '05; Chacko, Nomura, Papucci, Perez '05; Falkowski, Pokorski, Schmaltz '06; Chang, Hall, Weiner '06; Burdman, Chacko, Harnik '06; Foot, Volkas '06; Poland, Thaler '08; Harnik, Wizansky '08; Batra, Chacko '08; Cai, Cheng, Terning '08; NC, Englert, McCullough '13; Chacko, Cui, Hong '13; NC, Howe '13; NC, Knapen, Longhi '14; Geller, Telem '14; Burdman, Chacko, Harnik, Lima, Verhaaren '14; NC, Lou, McCullough, Thalapillil '14; NC, Katz, Strassler, Sundrum '15; Batell, McCullough '15; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15; NC, Katz '15; Garcia Garcia, Lasenby, March-Russell '15; Farina '15;]

A plethora of new naturalness-related signatures to look for @ LHC and beyond

(Hasn’t great for 750 GeV)

Much to look forward to throughout the lifetime of the LHC, even after ICHEP.
The Simplest Theory

The Mirror Twin Higgs
SM x SM x $Z_2$

[Z. Chacko, H.-S. Goh, R. Harnik '05]
Why not?
Higgs portal maintains equilibrium down to $T \sim \text{GeV}$

$\Delta N_{\text{eff}} >> 1$

Options are

- Change cosmology
  - Signals in BBN & CMB

- Change the spectrum
  - Copious new physics at $\sim \text{few TeV}$
  - Signals @ LHC

- Fraternal Twin Higgs
- Holographic Twin Higgs
- Composite Twin Higgs
- Orbifold Higgs
- …

See Roni’s talk
The Fraternal Twin

The “natural SUSY” of Twin Higgs

Just $Z_2$ partner states for the third generation, float couplings not crucial for naturalness

See also: [Geller, Telem ’14, Barbieri, Greco, Rattazzi, Wulzer ’15; Low, Tesi, Wang ’15]

Exotic Higgs Decays

• Twin sector must have twin QCD, confines around QCD scale

• Higgs boson couples to bound states of twin QCD

• Various possibilities. Glueballs at bottom of spectrum, lightest has same quantum # as Higgs

\[
\mathcal{L} \supset -\frac{\alpha_3'}{6\pi} v \frac{h}{f} G'_{\mu\nu} G'_{\alpha\mu\nu}
\]

Produce in rare Higgs decays (BR\(\sim 10^{-3}-10^{-4}\))

\[gg \rightarrow h \rightarrow 0^{++} + 0^{++} + \ldots\]

Decay back to SM via Higgs

\[0^{++} \rightarrow h^* \rightarrow f f\]

Long-lived, decay length is macroscopic; length scale \(\sim\) LHC detectors

[NC, Katz, Strassler, Sundrum '15; Curtin, Verhaaren '15; Chacko, Curtin, Verhaaren '16]
Fraternity & its discontents

*Fraternal Twin analogy with Natural SUSY is imperfect*

- Twin sector also chiral! Symmetry breaking is hard, not soft.
- Limited freedom for twin fermion masses. \[ \delta m^2_H \propto (\tilde{y}^2 - y^2)\Lambda^2 \]
- Need a picture for physics at cutoff.
- Inessential baggage (leptons) from anomaly cancellation.

**What if the twin sector were vector-like?**

Still need to address physics @ cutoff *but*

- Preserve $Z_2$ in couplings (modulo running); breaking in spectrum now soft.
- More freedom in fermion masses, anomalies trivial, …
The Vector-like Twin

The usual (chiral twin) story:

\[-\mathcal{L} \supset -m^2 \left[ |H|^2 + |H'|^2 \right] + \lambda \left[ |H|^2 + |H'|^2 \right]^2 + \delta \left[ |H|^4 + |H'|^4 \right] + y_t H q u + y_t H' q' u' + \text{h.c.}\]

UV sensitivity at one loop:

\[-\mathcal{L}^{(1)} \supset \frac{\Lambda^2}{16\pi^2} \left( -6y_t^2 + \frac{9}{4} g_2^2 + 10\lambda + 6\delta \right) \left( |H|^2 + |H'|^2 \right)\]

\[\text{PNGB Higgs protected}\]
The Vector-like Twin

Now make twin fermions vector-like w/ mass terms:

$$-\delta \mathcal{L} = M_Q q' \bar{q}' + M_U u' \bar{u}'$$

No change in quadratic UV sensitivity from vector-like masses; only log-divergent correction

$$\delta m_{h}^{2} \sim \frac{3y_t^2}{4\pi^2} \left( M_Q^2 \log \left[ \frac{M_Q^2}{\Lambda^2} \right] + M_U^2 \log \left[ \frac{M_U^2}{\Lambda^2} \right] \right)$$

$$\delta m_{h}^{2} \sim \frac{-y_t}{2f}$$

$$+ \frac{M_Q}{M_Q^\dagger} \frac{y_t f}{M_Q^\dagger}$$

$$+ \cdots$$
The Fine Print

- Need to forbid “wrong” yukawa couplings:
  \[ \mathcal{L} \supset \tilde{y}_t H^\dagger \tilde{q}' \tilde{u}' + \text{h.c.} \]
  No biggie: holomorphy, locality, softly broken PQ symmetry,…

- Need to suppress irrelevant operators:
  \[ \mathcal{L} \supset c \frac{M_Q}{\Lambda^2} H H^\dagger \tilde{q}' \tilde{q}' + \text{etc} \Rightarrow \delta m_h^2 \sim \frac{c}{16\pi^2} M_Q^2 \]
  Perturbative UV completion or locality or just \( M_Q \) not too large

- Couplings run differently below cutoff:
  \[ \beta_{g_3} = -7 \frac{g_3^3}{16\pi^2} \quad \beta_{g'_3} = -3 \frac{g'_3^3}{16\pi^2} \]
  Doesn’t spoil UV sensitivity, does require \( Z_2 \) restored at cutoff
A Simple Completion

Supersymmetrize it, compositize it, put it in an extra dimension...

Higgs quiver to diagonal around ~5-10 TeV

Amusing features: flavor texture, vector-like mass texture

\[
c_d d' \phi_T \bar{d}' + c_\ell \ell' \phi_D \bar{\ell}' + \frac{c_q}{\Lambda'} q' \phi_T \phi_D \bar{q}' + \frac{c_u}{\Lambda'} u' \phi_T \phi_T \bar{u}' + \frac{c_e}{\Lambda'} e' \phi_D \phi_D \bar{e}' \Rightarrow M_{D,L} \sim \Lambda, \ M_{Q,U,E} \sim \Lambda^2 / \Lambda'
\]
A minimal model

<table>
<thead>
<tr>
<th>$SU(3)'$</th>
<th>$SU(2)'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q'$</td>
<td>$\bar{q}'$</td>
</tr>
</tbody>
</table>

(look, ma, no leptons!)

Three Dirac mass eigenstates:

$$b'_1, t'_1, t'_2$$

$$m_{b_1} = M_Q \quad \mathcal{M}_{t_1,t_2} = \begin{pmatrix} M_Q & 0 \\ \frac{y_t f}{\sqrt{2}} & M_U \end{pmatrix}$$

Mini see-saw for $y_t f \gtrsim M_Q, M_U$

$$m_{t_1}^2 \approx 2\frac{M_Q^2 M_U^2}{y_t^2 f^2} \quad m_{t_2}^2 \approx \frac{1}{2} y_t^2 f^2 + M_Q^2 + M_U^2$$

Spectrum still very "fraternal":

raise twin $b$, lower twin $t_1$

Tuning: $\Delta = \frac{f^2}{2v^2} + \text{threshold}$

$$m_{t_1} \ (m_{b_1} = M_Q, \ m_{t_2} \sim 500 \text{ GeV})$$

Excluded by $h \rightarrow t'_1 t'_1$
Spectrum, features much like fraternal twin

Rare Higgs decays to glueballs, bottomonia; these undergo displaced decay back to SM, often on LHC length scales

Some novelties:

- No twin leptons, so both glueballs & onia must decay visibly
- $W'$ may be stable (dark matter?) if $W'\rightarrow t_1'b_1'$ closed
- $t_2'\rightarrow t_1'h$ if twin weak decays $t_2'\rightarrow W'b_1'$ closed
“Is neutral naturalness the beautiful reason we haven’t seen anything, or the last desperate hope of theorists?”

–G. Giudice

Above my pay grade, but at the very least: discrete symmetries have the same parametric freedom as “Natural SUSY” or your other favorite models.

If you do not find it beautiful, I leave you to Roni’s talk.
Looking forward...
“Outmaneuver Rattazzi”

Does UV-complete neutral naturalness always give SM-charged states at two loops?

\[ m_H^2 \sim \left( \frac{1}{16\pi^2} \right) \frac{3y_t^2}{8\pi^2} m_{\text{color}}^2 \]

If so, guaranteed collider bound on neutral naturalness

<table>
<thead>
<tr>
<th>SUSY Twin Tuning “Boost”: ( \frac{\lambda_{SM}}{\lambda} )</th>
<th>Composite Twin Tuning “Boost”: ( \frac{y_t^2}{g^2} )</th>
</tr>
</thead>
</table>

E.g. in SUSY Twin \( \Delta \sim \frac{\tilde{m}^2}{\lambda f^2} \times \frac{f^2}{v^2} = \frac{\tilde{m}^2}{m_H^2} \frac{\lambda_{SM}}{\lambda} \)

But: parametrics change if we can eliminate \( f^2/v^2 \) tuning
Rattazzi Outmaneuvered?

1. \( v/f \) tuning due to \( Z_2 \) symmetry; fix with hard \( Z_2 \)-breaking quartic

\[
(\delta_A |H_A|^4 + \delta_B |H_B|^4)
\]

Then vev flops into sector w/ smaller quartic:

\[
\frac{v_A^2}{v_B^2} \propto \frac{\delta_B}{\delta_A}
\]

[Chang, Hall, Weiner '06; Redigolo et al '16]

2. Instead of perturbing symmetric vacuum w/ mass vs. quartic, perturb asymmetric vacuum w/ mass vs. tadpole

[Beauchesne, Earl, Gregoire '15; Harnik, Howe, Kearney '16]
Totally neutral scalars?

In Twin Higgs, always have $v^2/f^2$ Higgs coupling deviations. Could avoid this smoking gun w/ scalar top partners.

In folded SUSY, common SU(2) factor:

$$\mathcal{L} \ni \lambda_t H_u q_3^A u_3^A + \lambda_t^2 |H_u \cdot \tilde{q}_3^B|^2 + \lambda_t^2 |H_u|^2 |\tilde{u}_3^B|^2$$

so F-stops are electroweak states; bounds from Drell-Yan production.

Is it possible to arrange for completely neutral scalar top partners?

$$\lambda_t H_u q_3^A u_3^A + \lambda_t^2 |H_u|^2 |\tilde{q}_3^B|^2 + \lambda_t^2 |H_u|^2 |\tilde{u}_3^B|^2$$

Need to get the scalar potential without an SU(2) contraction

$$\begin{pmatrix} H_u & \cdot \\ \cdot & X \end{pmatrix} \begin{pmatrix} \cdot \\ \tilde{q}_3^B \end{pmatrix}$$

Not impossible; start w/ larger parent symmetry and judicious orbifold projection.
Turtles?
[Batra, Kaplan]

Is there an alternative UV completion to SUSY/compositeness? Perhaps without colored states at two loops?

SUSY/CHM

\[ \begin{align*}
100 \text{ TeV} & \quad SU(4) \times U(1) \\
10 \text{ TeV} & \quad \langle \phi \rangle \sim 1 \text{ TeV} \\
1 \text{ TeV} & \quad SU(2) \times U(1) \\
.1 \text{ TeV} & \quad \langle H \rangle \sim .1 \text{ TeV}
\end{align*} \]

\[ \begin{align*}
100 \text{ TeV} & \quad SU(12) \times U(1) \\
10 \text{ TeV} & \quad \langle \chi \rangle \sim 10 \text{ TeV} \\
1 \text{ TeV} & \quad SU(4) \times U(1) \\
.1 \text{ TeV} & \quad \langle H \rangle \sim .1 \text{ TeV}
\end{align*} \]

\[ \text{N grows with each level; couplings rapidly grow strong.} \]

\textit{Unless} theory has good large-$N$ behavior, i.e. 't Hooft couplings $Ng^2$, $Ny^2$, $N\lambda^2$ remain under control. Plausible, no examples yet…
Embrace accidents

What if discrete symmetries of neutral naturalness are accidental symmetries of IR fixed point?

E.g. accidental supersymmetry [Sundrum]

IR theory contains SM + scalars

\[ \lambda_t HQ_3 \bar{u}_3 \quad \lambda_\phi |H|^2 |\phi|^2 \]

Strong dynamics drives

\[ \lambda_\phi \sim \lambda_t^2 \]

Neutral naturalness still lacks a “beautiful” theory, perhaps accidental symmetries are the way.
Conclusions

• Neutral naturalness: a response to data that is alive and well in our post-750 GeV world.

• Clearly an excellent signal generator; excellent motivation for new searches at LHC.

• More recently: discrete symmetries offer the same parametric freedom as natural SUSY.

• Many opportunities for exploration; likely we’ll discover more surprising and delightful ideas.