Naturalness of the electroweak scale?

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Pheno 2016
Elementary scalars are quadratically sensitive to physics at higher scales.

Independent of regularization scheme.

Model-building scales aside, gravity attests to presence of a higher scale.

No viable proposals for mitigating sensitivity to physics @ Planck scale without new physics @ weak scale.

Hierarchy problem only sharpened with the discovery of an elementary SM-like Higgs (+nothing else so far).
Natural vs. unnatural

Hierarchy problem is not a "just-so story"

<table>
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<tr>
<th>Field</th>
<th>Symmetry as $m \to 0$</th>
<th>Implication</th>
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<tr>
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<td>$m \Psi \bar{\Psi}$</td>
<td>$\Psi \to e^{i\alpha \gamma_5} \Psi$ (chiral symmetry)</td>
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What’s the scale?

The hierarchy problem is sensitivity to higher scales; quantify sensitivity of Higgs mass to new physics via ratio

\[ \Delta \equiv \frac{2\delta m_H^2}{m_h^2} \]

A *guidepost* to where new physics should enter; in the SM with a uniform cutoff \( \Lambda \), SM loops up to \( \Lambda \) give

\[ \delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2} \left[ 6\lambda(\mu) + \frac{9}{4} g_2^2(\mu) + \frac{3}{4} g_Y^2(\mu) - 6\lambda_t^2(\mu) \right] \]

Expect new physics to enter and alter SM at some scale*

\( \Delta \lesssim 1 \) (no tuning) requires \( \Lambda \lesssim 500 \text{ GeV} \);
\( \Delta \lesssim 10 \) (10%-level tuning) requires \( \Lambda \lesssim 1.6 \text{ TeV} \);
\( \Delta \lesssim 100 \) (1%-level tuning) requires \( \Lambda \lesssim 5 \text{ TeV} \).

*Best-case scenario, no large logs

See also X. Tata
The naturalness strategy

This is a *strategy* for new physics near $m_h$, not a *no-lose theorem*, because the theory does not break down if it is unnatural.

But naturalness has often been a very *successful* strategy.

E.g. charged pions

Electromagnetic contribution to the charged pion mass sensitive to the cutoff of the pion EFT.

$$\delta m^2 \sim \frac{3e^2}{16\pi^2} \Lambda^2$$

Naturalness suggests $\Lambda \sim 850$ MeV.
Rho meson (new physics!) enters at 770 MeV: $\Delta \sim 1$
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A physics driver @ LHC

170 of these 226 channels tied to naturalness
Hierarchy Solutions

Extend the SM with a symmetry acting on the Higgs

Supersymmetry

Supersymmetry
Sparticles $\tilde{m}$

$\approx 4\pi/G$

Higgs $m_h$

See also X. Tata

Global symmetry

Global-symmetry
Partner particles $\tilde{m}$

$\approx 4\pi/G$

Higgs $m_h$

See also A. Pomarol
New particles

Continuous symmetries commuting w/ SM
→ partner states w/ SM quantum numbers

Supersymmetry
\[ \phi \rightarrow \phi + \epsilon \psi \]
\[ \psi \rightarrow \psi + c^\mu \partial_\mu \phi \]
Opposite-statistics partner for every SM particle

Contribute to the Higgs mass:
\[ m_h^2 \sim \frac{3y_t^2}{4\pi^2} \tilde{m}^2 \log(\Lambda^2/\tilde{m}^2) \]

Global symmetry
\[ \Phi \rightarrow (1 + i\alpha T)\Phi \]
Same-statistics partner for every SM particle
Two spectra

5 TeV

Supersymmetry

Global symmetry

Simple game for LHC: look for colored partners.
Missing top partner problem
LHC searches driven by top partners

Global Symmetry

Supersymmetry

CMS preliminary $\sqrt{s} = 8$ TeV 19.6 fb$^{-1}$

Observed T Quark Mass Limit [GeV]

Problem 1: nothing yet (~0.1-10% tuning).
Problem 2: not much new to do.
Naturalness being so desirable a gift that we cling to supersymmetry in spite of the absence of experimental evidence.
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NATURALNESS WITHOUT SUPERSYMMETRY?

I. JACK and D.R.T. JONES
DAMTP, University of Liverpool, Liverpool L69 3BX, UK

Received 17 October 1989; revised manuscript received 27 October 1989
But: is this all there is?
Discrete symmetries

Discrete symmetry

Neutral partners $\tilde{m}$

$\leq 4\pi/G$

Higgs $m_h$

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”
The Twin Higgs

[Z. Chacko, H.-S. Goh, R. Harnik '05]

Proof of principle

Symmetry is $\text{SM}_A \times \text{SM}_B \times Z_2$
The Twin Higgs

Consider a scalar $H$ transforming as a fundamental under a global SU(4):

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

Potential leads to spontaneous symmetry breaking,

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

$SU(4) \rightarrow SU(3)$ yields seven goldstone bosons.

UV: $\lambda \gg 1$ NLSM; $\lambda \ll 1$ LSM
The Twin Higgs

Now gauge $SU(2)_A \times SU(2)_B \subset SU(4)$, w/ 

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

Then 6 goldstones are eaten, leaving one behind.

Explicitly breaks the $SU(4)$; expect radiative corrections.

$$V(H) \supset \frac{9}{64\pi^2} \left( g_A^2 \Lambda^2 |H_A|^2 + g_B^2 \Lambda^2 |H_B|^2 \right)$$

But these become $SU(4)$ symmetric if $g_A = g_B$ from a $Z_2$

Quadratic potential has accidental $SU(4)$ symmetry.
The Twin Higgs

Now gauge SU(2)\textsubscript{A} \times SU(2)\textsubscript{B} \subset SU(4), w/ \[ H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \]

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Explicitly breaks the SU(4); expect radiative corrections.

\[ V(H) \supset \frac{9}{64\pi^2} g^2 \Lambda^2 \left( |H_A|^2 + |H_B|^2 \right) \]

But these become SU(4) symmetric if \( g_A = g_B \) from a \( Z_2 \) Quadratic potential has accidental SU(4) symmetry.
The Twin Higgs

Achieve this protection for the entire SM by \( \text{SM}_A \times \text{SM}_B \times Z_2 \)

\( \text{SM}_A = \text{us}, \, \text{SM}_B = \text{twin sector} \)

Crucially:

\[
\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B
\]

\[
V(H) \supset \frac{\Lambda^2}{16\pi^2} \left(-6y_t^2 + \frac{9}{4}g^2 + \ldots\right) (|H_A|^2 + |H_B|^2)
\]

One-loop \( Z_2 \)-preserving, \( SU(4) \)-breaking quartic:

\[
V \supset \delta (|H_A|^4 + |H_B|^4) \quad \delta \sim \frac{y_t^4}{16\pi^2} \log(\Lambda/f)
\]

(only quadratic insensitivity to cutoff)
The Twin Higgs

Naive vacuum: \[ \langle H_A \rangle^2 = \langle H_B \rangle^2 = \frac{f^2}{2} \]

\( f \) is not far from \( v \), and the cutoff is \( \sim \text{TeV} \). Not much of a protection, and \( O(50\%) \) deviations in Higgs couplings.
The Twin Higgs

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Option 1: softly break \( Z_2 \)

\[ V_{soft}(H) = \delta m_H^2 |H_A|^2 \]

Allows \( v \ll f \), at the price of a tuning \( \sim O(f^2/2v^2) \)
The Twin Higgs

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Option 2: hard breaking of \( Z_2 \) \[ V_{hard}(H) = \delta_{A,B} |H_{A,B}|^4 \]
The Twin Higgs

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Option 3: tadpole breaking of \( Z_2 \) [Beauchesne, Earl, Gregoire ’15]
The Twin Higgs

\[ \mathcal{O}(v/f) \]

\[ \Lambda \lesssim 4\pi f \]

\[ \sqrt{\lambda}f \]

\[ f \]

\[ h_B \]

\[ t_B \]

\[ v \]

\[ \Lambda \]

\[ v_A \]

\[ t_A \]
The Twin Top

The top partner acts as we expect from global symmetry protection, but is not charged under QCD.

\[ \mathcal{L} \supset -y_t H_A Q^A_3 \bar{u}^A_3 - y_t H_B Q^B_3 \bar{u}^B_3 \]

\[ h + \ldots \quad \quad f - \frac{h^2}{2f} + \ldots \]

Symmetry protecting the Higgs takes us into a different SU(3) group. No direct limit on top partners.
“Neutral” naturalness

Simplest theory: exact mirror copy of SM
[Chacko, Goh, Harnik ’05]

But this is more than you need, and mirror 1st, 2nd gens lead to cosmological problems

Many more options where symmetry is approximate, e.g. a good symmetry for heaviest SM particles.
[NC, Knapen, Longhi ’14; Geller, Telem ’14; NC, Katz, Strassler, Sundrum ’15; Barbieri, Greco, Rattazzi, Wulzer ’15; Low, Tesi, Wang ’15, NC, Knapen, Longhi, Strassler ’16]
Finding a mirror

No longer produce partner particles through strong interactions

- Partner states are SM neutral, couple only to the Higgs. Lighter than $m_h/2$: modest invisible Higgs decays.
- Heavier than $m_h/2$: produce through an off-shell Higgs.

Hard but very interesting; directly probe naturalness

95% Exclusion

$\sqrt{s} = 14$ TeV

[NC, Lou, McCullough, Thalapillil ‘14]
In SM, Higgs is a fluctuation around its vacuum expectation value.

In twin theories, Higgs is misaligned with the VEV by a small amount.

Gives universal shift in Higgs couplings.

Current bounds place twin sector $\sim 3 \times$ SM scale.

Interesting for LHC Run 2 but unlikely to improve much.
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 most interesting; have same quantum # as Higgs

\[ \mathcal{L} \supset -\frac{\alpha'_3}{6\pi} \frac{v}{f} G_{\mu\nu}' \epsilon_{\mu\nu}\ ]\ G'_{\mu\nu} \]

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

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

Decay back to SM via Higgs

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

Long-lived, decay length is macroscopic; length scale ~ LHC detectors

[NC, Katz, Strassler, Sundrum ’15; Curtin, Verhaaren ’15; Chacko, Curtin, Verhaaren ’16]
Looking for displaced decays

Run 1 searches at LHC in right direction but not sensitive
Compelling prospects for Run 2…

[Csaki, Kuflik, Lombardo, Slone, ’16]
### Partner quantum #s

<table>
<thead>
<tr>
<th></th>
<th>Global</th>
<th>SUSY</th>
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<tbody>
<tr>
<td>QCD x EWK</td>
<td>Composite / Little Higgs</td>
<td>MSSM</td>
</tr>
<tr>
<td>Neutral x EWK</td>
<td>Quirky Little Higgs</td>
<td>Folded SUSY</td>
</tr>
<tr>
<td>Neutral x Neutral</td>
<td>Twin Higgs</td>
<td>???</td>
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A plethora of new naturalness-related signatures to look for @ LHC and beyond

Much to look forward to at LHC Run 2
Not symmetries?

What if the weak scale is selected by **dynamics**, not symmetries?

Old idea: couple Higgs to field whose minimum sets \( m_H = 0 \)
Old problem: How to make \( m_H = 0 \) a special point of potential?

New solution: what turns on when \( m_H^2 \) goes negative?

\[ V(\phi) \]

**Vev** gives **quark masses** which give **axion potential**!

“Relaxion”

[Graham, Kaplan, Rajendran ‘15]
\[ (-M^2 + g\phi)|H|^2 + V(g\phi) + \frac{1}{32\pi^2} \frac{\phi}{f} \tilde{G}^{\mu\nu} G_{\mu\nu} \]
\[ \Rightarrow (-M^2 + g\phi)|H|^2 + V(g\phi) + \Lambda^4 \cos(\phi/f) \]

**But:** immense energy stored in rolling field, still need to stop.

**Inflation** is a good source of friction.

**Just need Higgs + non-compact axion + inflation w/**

- Very low Hubble scale \((\ll \Lambda_{\text{QCD}})\)
- 10 Giga-years of inflation

*Warning: likely just transferring fine-tuning to inflationary sector.*
[Di Chiara, Kannike, Marzola, Racciopi, Raidal, Spethmann '15; Fowlie, Balasz, White, Marzola, Raidal '16]

**Minimal model:** cutoff is

\[ M < \left( \frac{\Lambda^4 M_P^3}{f} \right)^{1/6} \theta^{1/4} \sim 30\text{ TeV} \times \left( \frac{10^9\text{ GeV}}{f} \right)^{1/6} \left( \frac{\theta}{10^{-10}} \right)^{1/4} \]

In vacuum, axion gives \(O(1)\) contribution to \(\theta_{\text{QCD}}\)

See also: [Espinosa, Grojean, Panico, Pomarol, Servant '15; Hardy '15; Gupta, Komargodski, Perez, Ubaldi '15; Batell, Giudice, McCullough '15]
Not symmetries?

Fix: make it someone else’s QCD + axion

### Field

<table>
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<tr>
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<th>$SU(3)_N$</th>
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I.e. axion of a different SU(3); need to tie in Higgs vev

1. New quarks must get most of mass from Higgs:

$$\mathcal{L} \supset m_L LL^c + m_N NN^c + y H L N^c + y' H^+ L^c N$$

2. Must confine, but with light flavor \( \Lambda^4 \approx 4\pi f_\pi^3 m_N \)
...still new physics @ weak scale

Now \[ m_N \geq yy'v^2/m_L \] (smallest see-saw mass from EWSB if L heavy)

But also \[
\begin{align*}
m_N \geq \frac{yy'}{16\pi^2}m_L \log(M/m_L) \\
m_N \geq yy'f_\pi'/m_L
\end{align*}
\] (Radiative Dirac mass) (Higgs wiggles biggest)

These bounds imply \( f_{\pi'} < v \) and \( m_L < \frac{4\pi v}{\sqrt{\log(M/m_L)}} \)

Can’t decouple new degrees of freedom.
New confining physics near weak scale!

Couples to Higgs; hidden valley signatures

\[ M < \left( \frac{\Lambda^4 M_P^3}{f} \right)^{1/6} \sim 3 \times 10^5 \text{ TeV} \times \left( \frac{10^9 \text{ GeV}}{f} \right)^{1/6} \left( \frac{f_{\pi'}}{30 \text{ GeV}} \right)^{1/2} \left( \frac{yy'}{10^{-2}} \right)^{1/6} \left( \frac{300 \text{ GeV}}{m_L} \right)^{1/6} \]
The 750 GeV elephant in the room

**Supersymmetry**

**RPV sneutrino**
[Allanach, Dev, Renner, Sakurai 1512.07645]

\[
\Gamma(\phi \to \gamma\gamma) = \frac{(m^2_\nu + m^2_\tau + m^2_\chi)M^3_\phi}{32\pi F^2}
\]

**Sgoldstino**
[Petersson, Torre 1512.05333]

**Sbino (dirac gauginos)**
[Carpenter, Colburn, Goodman 1512.06107]

\[
\begin{pmatrix}
\psi & A_\mu & \lambda \\
\end{pmatrix}
\]

**Extra dimensions**

**KK graviton**
[Giddings, Zhang 1602.02793]

[Tension with dileptons]

**Radion**
[Ahmed, Dillon, Grzadkowski, Gunion, Jiang]

Hard to match rate, incalculable?

**Compositeness**

E.g. \(SO(6) \to SO(5) \to SO(4)\)
[No, Sanz, Setford 1512.05700]

Generally expect heavy resonances + vector-like matter. Hard to understand lack of Higgs mixing.

**Relaxion**

Ingredients seem to be there (bifundamental matter, etc.)

Not sure what \(X(750)\) should be.

**Neutral naturalness**

Doesn’t want to be a twin Higgs due to Higgs mixing. Ingredients are there in a UV completion.

If \(X(750)\) is a (pseudo)scalar, electroweak tuning comparable to CC
## Conclusion

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• With new signatures and new possibilities, the verdict on weak-scale naturalness is still out. **Exciting times to be in the hunt!**

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