Electroweak Symmetry Breaking after the first hints of a Higgs

Riccardo Rattazzi
What is the dynamics of Electroweak Symmetry Breaking?

Was the hierarchy problem a good problem?

Is Dark Matter made of weakly interacting thermal relics?

Why is the electron much lighter than the top quark?

Why 3 families?
\[ m_{W,Z} \neq 0 \quad \text{3 polarizations} = 2 \perp + 1 \parallel \]

not “pure” gauge int

\[ \mathcal{A}(V_L V_L \rightarrow V_L V_L) = \frac{\sqrt{s}}{174 \text{ GeV}}^2 \]

New strong force at 2 TeV!

- EWSB implies new stuff below \( \sim 2 \text{ TeV’s} \)
- Simplest option (or so it seems): just the Higgs boson

\[ \frac{m_h^2}{v^2} \]

weak up to ultra-high scale

SM with Higgs boson can be extrapolated virtually to \( E \sim M_{Pl} \)
SM as an effective theory

- beautifully simple
  - it explains
    - $B,L$ approx conservation
    - small neutrino masses
  - nicely accounts for
    - small flavor violation
    - electroweak precision tests
- and it has a beautiful theoretical problem
The hierarchy problem

\[ V(H) = \epsilon \Lambda_{UV}^2 H^2 + \lambda H^4 \]

but we need

\[ \langle H \rangle = \sqrt{\epsilon} \Lambda_{UV} \]

\[ \epsilon \sim 10^{-34} \]

generically

\[ \epsilon \sim -O(1) \]

\[ \langle H \rangle \sim \Lambda_{UV} \]
same tuning to reach boundary of 2nd order phase transition

How did nature choose to deal with hierarchy problem?
same tuning to reach boundary of 2\textsuperscript{nd} order phase transition

\[ \epsilon \sim 10^{-34} \]

How did nature choose to deal with hierarchy problem?

stolen from V. Rychkov
I
Supersymmetry

II
Strong EWSB dynamics (composite Higgs)

III
Large Extra Dimensions

IV
Multiverse (anthropic principle)

$10^{10^0} \ldots$ vacua
of which many have a hierarchy

Expect: just SM + Higgs
+ (possibly weak scale DM)

see NYT Op-Ed
Cardinal Schönborn
The more natural the theory the more the Higgs rates deviate from SM
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first probes into EWSB dynamics and into hierarchy puzzle

\[ 115 \text{ GeV} \lesssim m_h \lesssim 130 \text{ GeV} \]

lucky range to measure all couplings

It would be useful to develop a ‘Higgs diagnostic’: associate the possible patterns of deviation to broad/specific features of the underlying theory
Can use effective lagrangian to describe deviations from SM

= simple parametrization encompassing a large class of models
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= simple parametrization encompassing a large class of models
I. Strong EWSB dynamics = ‘Composite Higgs’

II. Supersymmetry

III. Anthropic and all that
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compositeness scale

TeV

New strong

$W_L^\pm, Z_L^0 + \star$

$q, \ell, \gamma, W_T, Z_T, g$

$M_{\text{Planck}}$?
Compositeness scale

TeV

New strong

$W_L^\pm, Z_L^0 + \star$

$q, \ell, \gamma, W_T, Z_T, g$

**Technicolor** $\text{SO}(4)/\text{SO}(3)$:  \( \star = \text{nothing} \)

Not feeling too well

**pseudo-NG Higgs** $\text{SO}(5)/\text{SO}(4)$:  \( \star = h \)

\[ W_L^\pm, Z_L^0, h \rightarrow \begin{pmatrix} H^+ \\ H_0 \end{pmatrix} \]

extended cosets $\text{SO}(6)/\text{SO}(5)$, $\text{SO}(6)/\text{SO}(4) \times \text{U}(1)$: additional light scalars

**pseudo-dilaton**: \( \star = \chi \)

does not fit in $\text{SU}(2)$ doublet
The main advantage of pseudo-NG Higgs

\[ S = S_{TC} \times \frac{v^2}{f^2} \]

\[ f = \text{Goldstone decay const} \]

EWPT are OK with mild tuning

\[ \frac{v^2}{f^2} \sim 0.1 - 0.3 \]

- Compositeness scale \( 4\pi f \) still as low as a few TeV
- Sizeable corrections to Higgs couplings: \( O\left(\frac{v^2}{f^2}\right) \)
- Direct signatures
  - Production of resonances
  - Strong WW scattering

Georgi, Kaplan ‘84
Arkani-Hamed, Cohen, Katz, Nelson ‘02
Agashe, Contino, Pomarol ‘04

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The main advantage of pseudo-NG Higgs

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General parametrization of \textit{Higgslike scalar }$h$

\textit{Contino, Grojean, Moretti, Piccinini, RR’10}

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 + \frac{M_V^2}{2} \text{Tr} (V_\mu V^\mu) \left[ 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right] - m_i \bar{\psi}_{Li} \left( 1 + \frac{c h}{v} \right) \psi_{Ri} + \text{h.c.} \]

\[ + \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6} \left( \frac{3m_h^2}{v} \right) h^3 + d_4 \frac{1}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 + \ldots \]

\[ + c_g \frac{\alpha_s}{4\pi} \frac{h}{v} G_{\mu\nu} G^{\mu\nu} + c_\gamma \frac{\alpha}{4\pi} \frac{h}{v} F_{\mu\nu} F^{\mu\nu} \]

\textit{C} flavor universal in minimal flavor violating set up

\begin{itemize}
  \item Standard Model: $a = b = c = d_3 = 1$
  \item $c_g = c_\gamma = 0$
  \item $h$ = pseudo-Goldstone implies additional constraints
\end{itemize}
SO(5)/SO(4) Pseudo-Goldstone Higgs

\[ a = \sqrt{1 - v^2/f^2} \quad b = 1 - 2v^2/f^2 \]  
\[ c = d_3 = \sqrt{1 - v^2/f^2} \quad c = d_3 = \frac{1 - 2v^2/f^2}{\sqrt{1 - v^2/f^2}} \]

fermions in 4 \quad fermions in 5

\[{c_g, \ c_\gamma} \sim \frac{\alpha_t}{4\pi}\] controlled by small explicit SO(5) breaking

NEGLIGIBLE!

Interesting inequalities

\[ 0 \leq a, \ |b| \leq 1 \] robust

\[ 0 < c < 1 \] in range favored by EWPT
In specific models just one free parameter \[ \xi \equiv \frac{v^2}{f^2} \]

In general 4 parameters \[ a, c_t, c_b, c_\tau \]

\[ \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)|_{SM}} = \frac{\Gamma(h \to tt)}{\Gamma(h \to tt)|_{SM}} = c_t^2 \]

\[ \frac{\Gamma(h \to f\bar{f})}{\Gamma(h \to f\bar{f})|_{SM}} = c_f^2 \]

\[ \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)|_{SM}} = a^2 \left[ 1 + 0.28(1 - c_t/a) \right]^2 \sim a^2 \]

\[ \frac{\Gamma(h \to VV)}{\Gamma(h \to VV)|_{SM}} = a^2 \]

In the preferred range all rates are reduced
We include now all the search channels for some representative mass points: 120, 130, 160, and 200, as above. Finally, the 125 GeV case should be treated separately.

Again we'd like to have an idea of the difference obtained when using the direct/indirect method of extracting the WW channel data. Below are the plots obtained first using our extrapolation, showing 99% CL exclusions. Following that is the same sort of plot, but with the WW data determined directly (constucting likelihood from wiki).

\[
C_t = C_b = C_\tau \equiv C
\]
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Can increase $R_{\gamma\gamma}$, but at the price of $R_{bb}$
\[ \frac{v^2}{f^2} \ll 1 \]  

**SILH effective lagrangian**

\[ \mathcal{L}_{\text{eff}} = \frac{c_H}{2f^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + y_f \frac{c_y}{f^2} H^\dagger H \bar{\psi}_L H \psi_R - \frac{c_6 \lambda}{f^2} (H^\dagger H)^3 \]

\[ 0 \leq a, b, c \leq 1 \quad \quad c_H, c_y > 0 \]  

true in larger class including Little Higgs
A dispersion relation for $c_H$

$$c_H = \frac{f^2}{\pi} \int_0^\infty (\sigma_{+-}(s) - \sigma_{++}(s)) \frac{ds}{s}$$

$H^+ \quad \text{anything} \quad H^+$

$H^- \quad \text{anything} \quad H^+$

$c_H$ not positive definite, but almost so

$\Delta c_H > 0$

$\Delta c_H < 0$

Scalar triplets do not dominate in known models addressing hierarchy
Other roads to increase Higgs couplings

\[
\begin{align*}
 a &= \sqrt{b} = c = \frac{v}{f_D} \\
 d_3 &= \frac{5}{3} \frac{v}{f_D} + O(\epsilon) \\
 c_g, c_\gamma &= O(v/f_D)
\end{align*}
\]

Dilaton

\[
H \in SO(4,1)/SO(4)
\]

Non-Compact coset space

\[
\begin{align*}
 a &= \sqrt{1 + \frac{v^2}{f^2}} \\
 b &= 1 + 2\frac{v^2}{f^2}
\end{align*}
\]

No Unitary QFT as UV completion \(\rightarrow\) TeV scale Quantum Gravity?
$m_h, m_t$ and colored resonances

$y_t \sim \frac{y_L y_R f}{M_T}$

$m_h < 130$ GeV $\quad \rightarrow \quad M_T \approx 1$ TeV $\left(\frac{0.5}{\frac{v}{f}}\right)$
Panico, Wulzer (preliminary)
LHC has already probed part of this plot:

CMS search of B:
\[ M_{X_{5/3}} > 490 \]

\[ M_{\tilde{T}} \]

\[ \xi = 0.2 \]

\[ m_H > 130 \]

\[ m_H \in [115, 130] \]

Panico, Wulzer (preliminary)
I. Strong EWSB dynamics = ‘Composite Higgs’

II. Supersymmetry

III. Anthropic and all that
Naturalness bound\[ \sqrt{\frac{m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2}{2}} \lesssim \frac{400 \text{ GeV}}{\sqrt{1 + X^2}} \left( \frac{3}{\ln \frac{\Lambda_{SUSY}}{\text{TeV}}} \right)^{\frac{1}{2}} \left( \frac{0.2}{\epsilon_T} \right)^{\frac{1}{2}} \]

tuning smallest for: small \[ X^2 = \frac{A^2}{m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2} \] & low \[ \Lambda_{SUSY} \]

High scale mediation \[ m_{\tilde{t}} \lesssim 100 \text{ GeV} \left( \frac{1}{\epsilon_T} \right)^{\frac{1}{2}} \]
ATLAS

bound on gluinos and squarks of 1st 2nd family

In simplest models $m_{\tilde{t}} \sim m_{\tilde{g}} \sim m_{\tilde{g}}$ it looks like 1% tuning
Squashed spectra slightly less constrained: less tuning

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Still less constrained with $\sim 1 \text{ fb}^{-1}$

$m_{\tilde{t}_L}, m_{\tilde{t}_R} \gtrsim 250 \text{ GeV}$

Papucci, Ruderman, Weiler ’11
The perspective changes appreciably if one buys the $m_h \sim 125$ GeV hint in MSSM to push up Higgs quartic one needs

- stop masses $\geq 1$ TeV
- large $A$-terms

worst that $1\%$ tuning + problematic for $b \rightarrow s\gamma$

\[ A_t/\sqrt{\langle m^2 \rangle} = 2.0, \tan\beta = 10, \mu = 200 \text{ GeV} \]
$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{(stop loops)}$$

Hall, Pinner, Ruderman ’11

stop masses $< 500$ GeV
small $A$
small $\tan \beta$

$O(10\%)$ tuning + ok for $b \rightarrow s \gamma$
An exercise in Higgs diagnostic

\[ H' = -\cos \beta H_2 + \sin \beta H_1 \]
\[ H = \cos \beta H_1 + \sin \beta H_2 \]
\[ \Delta c_H = 0 \]

dim 8 operator: quick decoupling in $h\gamma\gamma$ and $hWW$

sign depends on structure of quartic

MSSM \[ (H_1^2 - H_2^2)^2 \]
\[ c_b > 1 \]
\[ c_t < 1 \]

NMSSM \[ H_1^2 H_2^2 \]
\[ c_b < 1 \]
\[ c_t > 1 \]
\[ \lambda - \text{SUSY} = \text{NMSSM with } \lambda > 1 \]

cut-off is below GUT scale

\[ R_{\gamma\gamma}, R_{ZZ} > 1 \]

\[ R_{b\bar{b}} < 1 \]

\[ \lambda \text{ dominates the quartic} \]

\[ m_{H^+} = 350 \text{ GeV} \]
SM

generic MSSM

natural MSSM

NMSSM

$\lambda$-SUSY NMSSM

Technicolor

composite Higgs
perhaps, rather than naturalness, the guidelines should be

A) existence of a complex world (anthropic selection)
B) structure (Ex.: unification, strings)
C) cosmological obs: existence of Dark Matter, baryon asymmetry,...
D) minimality

✦ Split-SUSY (ABCD)

Ex  ✦ High-Scale SUSY (ABD)

✦ nuMSM (CD)

Arkani-Hamed, Dimopoulos ’04
Hall, Nomura ’10
Asaka, Blanchet, Shaposhnikov ’05
\( \lambda_h(M_P) \) curiously close to zero in RG extrapolated SM

- Is it just High-Scale SUSY at \( \tan \beta = 1 \)?
- Is the Higgs a pseudo-NG-boson, ... but at the Planck scale?
- Is there a deeper explanation (ex asymptotic safety)?

\text{Giudice, Strumia, '11}

\text{Shaposhnikov, Wetterich '10}

Would we ever know?
Split SUSY

\[ 10 \text{ TeV} \leq m_{\tilde{f}} \leq 10^4 \text{ TeV} \]

\[ \tau_{\tilde{g}} \simeq \left( \frac{\text{TeV}}{m_{\tilde{g}}} \right)^5 \left( \frac{m_{\tilde{f}}}{10^4 \text{ TeV}} \right)^4 \times 10^{-8} s \]

- search for displaced vertices from gluino decays
- compatible with ‘SUSY breaking without singlets’
  simplest anomaly mediated scenario

\[ m_{\tilde{f}} \sim m_{3/2} \sim 10^2 \text{ TeV} \]

\[ m_{\lambda_i} = \frac{\beta_i(g_i)}{2g_i^2} m_{3/2} \sim \text{ TeV} \]

Giudice, Luty, Murayama, Rattazzi ’98

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Natural Theory
unNatural Theory
unNatural Theory

- RG extrapolation
- speculation
- move to string theory
Back up slides
$A_t/\sqrt{\langle m^2 \rangle} = 1.0$, $\tan \beta = 10$, $\mu = 200$ GeV

- BR($B \to X_s \gamma$) at 2$\sigma$
- 1% FT
- No stops solution
- $m_2 < m_1$