What’s next after the HIGGS BOSON discovery?

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Particle Physics

What is the world made of? What holds it together?

Energy Frontier: $1\text{TeV} = 1000\text{ GeV}$

Standard Model

100 GeV $\leftrightarrow 10^{-16}\text{ cm}$

"nano — nano scale"
### THE STANDARD MODEL

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Fermions</th>
<th>Bosons</th>
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<td>c</td>
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**Force carriers**

<table>
<thead>
<tr>
<th>Leptons</th>
<th>W</th>
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*Higgs boson

Source: AAAS
Mass spectrum of elementary particles

- **FERMIIONS**
  - First Generation
  - Second Generation
  - Third Generation
  - Top quark
  - Bottom quark
  - Charm quark
  - Strange quark
  - Tau
  - Muon
  - Down quark
  - Up quark
  - Electron

- **BOSONS**
  - Z
  - W
  - Higgs

**MASSLESS BOSONS**
- Photon
- Gluon
- Graviton
Higgs discovery - LHC Run I

“I think we have it” Rolf-Dieter Heuer, CERN Director General, July 4, 2012

Higgs mass (ATLAS + CMS)

\[ m_h = 125.09 \pm 0.21 \text{(stat.)} \pm 0.11 \text{(syst.) GeV} \]

Higgs couplings

as expected in Standard Model!
The importance of the Standard Model Higgs

[Englert, Brout 1964; Higgs 1964; Guralnik, Hagen, Kibble 1964]

1. Generates elementary particle mass

- electron mass: 0.5 MeV
- Bohr radius \( a_0 = \frac{\hbar}{m_e c \alpha} \approx 0.53 \text{Å} \)
- existence of atoms
- quark masses: \( m_{\text{down}} > m_{\text{up}} \)
- \( m_{\text{neutron}} > m_{\text{proton}} \)
- stable proton

Higgs potential:

\[
V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4
\]

\[
\langle H \rangle = \frac{1}{\sqrt{2}} (v + h)
\]

- \( v^2 = \frac{\mu_h^2}{\lambda_h} \approx (246 \text{ GeV})^2 \)
- \( m_h^2 = 2\lambda_h v^2 \approx (125 \text{ GeV})^2 \)
- \( \mu_h \approx (89 \text{ GeV})^2 \)
- \( \lambda_h \approx 0.13 \)

no condensate
- photon
- electron
- top quark

vacuum condensate
- photon
- electron
- top quark

existence of atoms

Wednesday, 2 December 15
2. Restores perturbative unitarity

\[ \mathcal{A}(E) \sim \text{constant} \]

Unitarity is restored (perturbatively)!

Standard Model is valid up to the Planck scale!
However, the Standard Model is not a complete description of Nature?

Questions:
- Planck/weak scale hierarchy? \( \mu_h \ll M_P \)
- Fermion mass hierarchy? Neutrino masses?
- Dark matter?
- Baryon asymmetry?
- Strong CP problem?
- GUTS? Inflation?
- UV completion of gravity?
- Cosmological constant?

Clearly requires new physics... but why should any be near the electroweak scale?
Quantum corrections to Higgs mass:

\[ \mu_h^2 = a_0 \Lambda^2 - \frac{3 y_t^2 \Lambda^2}{16 \pi^2} \]

where \( \Lambda \) = proxy for massive particle scale in (finite) UV completion

Assuming \( \Lambda \simeq 10^{16} \text{ GeV} \) then \( \mu_h^2 \gg (100 \text{ GeV})^2 \) !!

Unless: \( \mu_h^2 \simeq (100 \text{ GeV})^2 \sim (10^{16} \text{ GeV})^2 - (10^{16} \text{ GeV})^2 \)

Requires tuning to 1 part in \( 10^{28} \)!!

Why is \( \mu_h \ll \Lambda \sim 10^{16} \text{ GeV} \)?

HIERARCHY PROBLEM
NATURAL explanations of ~125 GeV Higgs

HIGGS BOSON

Elementary → Supersymmetry

OR

Composite → New strong dynamics (Extra dimensions)
1. Supersymmetry (SUSY)

Cancel quadratic sensitivity with new spacetime symmetry:

\[ \mu_h^2 \simeq m_0^2 - \frac{3y_t}{16\pi^2} \Lambda^2 + \frac{3y_t^2}{16\pi^2} \Lambda^2 + \frac{3y_t^2}{16\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda^2}{m_{\tilde{t}}^2} \]

Thus, \( \mu_h \ll \Lambda \) provided \( m_{\tilde{t}} \lesssim \mathcal{O}(\text{TeV}) \)

Superpartners at the TeV scale!
**Bonus features:**

- Dark matter from lightest supersymmetric particle (LSP)
- Gauge coupling unification from Higgsinos, gauginos
- No obstacle to UV completion
- Light colored states (gluino, stop) can be produced at LHC
Impact of 125 GeV Higgs:

\[ V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4 \]

\[ (m_A \gg m_Z, \tan \beta \gg 1) \]

\[ \lambda_h = \frac{1}{8} (g^2 + g'^2) + \frac{3y_t^4}{64\pi^2} \left[ \ln \frac{m_t^2}{m_{\tilde{t}}^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left( 1 - \frac{X_t^2}{12m_{\tilde{t}}^2} \right) \right] \]

where \( X_t = A_t - \mu \cos \beta \)

\[ m_{\tilde{t}} \gtrsim 1 \text{ TeV} \quad (X_t \sim m_{\tilde{t}}) \]

\[ m_{\tilde{\ell}} \lesssim 400 \text{ GeV} \quad (\text{“natural”}) \]

\[ \lambda_h \simeq 0.13 \quad \mu_h^2 \simeq (89 \text{ GeV})^2 \]
red/blue bands = 124-126 GeV
Higgs mass contours

tuning = \frac{1}{\Delta m_h}

\Rightarrow \textbf{Tuning is } \lesssim 1\%
LHC Run-I Limits:

\[ m_{\tilde{g}} \gtrsim 1400 \text{ GeV} \]

\[ m_{\tilde{t}_1} \gtrsim 700 \text{ GeV} \]
Best case scenario “natural SUSY”

To minimize tuning:

(i) Low messenger scale \( \Lambda_{mess} = 20 \text{ TeV} \)

\[ \log \frac{\Lambda_{mess}}{m_i} \sim 3 \]

(ii) Add new contribution to Higgs quartic coupling

No need for heavy stop, A-term

(scale-invariant) NMSSM

\[ W_{\text{NMSSM}} = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \]

\( S = \text{singlet} \)

Higgs mass:

\[ m_h^2 = m_Z^2 \cos^2 2\beta + \frac{\lambda^2 v^2}{4} \sin^2 2\beta \]

new parameter to increase Higgs mass
How natural is “natural SUSY”? 

LHC Run I

\[ \text{natural SUSY} \sim 20\% \text{ has become} \ < 10\% \text{ tuning} \]

where

\[
\Lambda_{mess} = 20 \text{ TeV}
\]

\[
\Sigma^h \equiv \max_i \left| \frac{d \log m_h}{d \log \xi_i} \right|
\]

\[
\Sigma^\nu \equiv \max_i \left| \frac{d \log v^2}{d \log \xi_i(\Lambda_{mess})} \right|
\]
Gluino-stop masses

For tuning $\sim 5 - 10\%$

$m_{\tilde{g}} \lesssim 2 \text{ TeV} \quad m_{\tilde{t}_1} \lesssim 1.2 \text{ TeV}$

[Caveat: Bottom-up approach is naive sampling of parameter space -- tuning could be worse! ]
A consistent *natural* SUSY scenario based on Run1:

(i) weakly-coupled Higgs (∼125 GeV)

(ii) \(m(\tilde{q}_{1,2}) \gg m(\tilde{g}), m(\tilde{q}_3)\)

SUSY breaking is *flavour dependent*!

\(\Lambda_{UV} \sim M_P\)

\(m(\tilde{q}_{1,2}) \gg \text{TeV}\)

\(m(\tilde{q}_3), m(\tilde{g}) \lesssim 1.5 \text{ TeV}\)

\(m_h \sim 125 \text{ GeV}\)

“Split families”

[Dimopoulos, Guidice 95; Pomarol, Tommasini 95; Cohen, Kaplan, Nelson 96]
2. Compositeness/Extra dimensions

**HIERARCHY PROBLEM**

\[ \mu_h^2 = a_0 \Lambda^2 - \frac{3y_t^2}{16\pi^2} \Lambda^2 \]

If \( \Lambda \approx \text{TeV} \) \( \rightarrow \) mass correction \( \approx 100 \text{ GeV} \) \( \checkmark \text{O.K.} \)

Higgs boson no longer elementary at TeV scale!

**EITHER**

- Flat extra dimensions \( \rightarrow \) Quantum gravity/string theory at TeV scale!

**OR**

- Warped extra dimension \( \rightarrow \) Composite Higgs!
**Higgs as a pseudo Nambu-Goldstone boson**

[Georgi, Kaplan `84]

Global symmetry $G$ *spontaneously broken* to subgroup $H$ at scale $f$

$$
\rho^{(n)} \gtrsim \text{TeV}
$$

Resonance mass: $m_\rho \sim g_\rho f \quad 1 \lesssim g_\rho \lesssim 4\pi$

**Higgs mass protected by shift symmetry**

-- like pions in QCD

**BUT** global symmetry must be explicitly broken to generate $V(h) \neq 0$
Global symmetry broken by mixing with elementary sector

[Agashe, Contino, Pomarol 2004]

\[
\mathcal{L}_{\text{mix}} = \lambda_{L,R} \bar{\Psi}_{L,R} \mathcal{O}_{\Psi} + g_Y A^\mu J_\mu
\]

Higgs potential:

\[
V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4
\]

where \( \mu_h \sim \frac{g_{SM}^2}{16\pi^2} g \rho f^2 \), \( \lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g \rho^2 \)

EWSB \( \langle H \rangle = \frac{v}{\sqrt{2}} \)

\[
v^2 = \frac{\mu_h^2}{\lambda_h}
\]

Tuning: \( \Delta^{-1} \sim \frac{v^2}{f^2} \)
Higgs mass: 

\[ m_h^2 \simeq \frac{N_c}{\pi^2} m_t^2 \left( \frac{m_T^2}{f^2} \right) = g_T^2 \]

\[ m_T = \text{fermion resonance mass} \]

\[ m_T \sim m_\rho \gtrsim 2.5 \text{ TeV} \quad (g_T \sim g_\rho \gtrsim 3) \]

\[ m_h \gtrsim m_t \]

But, no need for \( m_T \sim m_\rho \)

\[ m_h \sim 125 \text{ GeV} \]

\[ m_T < m_\rho \]

light fermion resonances
**Bonus features:**

- Dark matter from singlet scalar
- Composite top quark can explain:
  -- fermion mass hierarchy
  -- gauge coupling unification
- Light fermion resonances can be produced at LHC
LHC Run-I Limits:

\[ m_T \gtrsim 600 \text{ – } 800 \text{ GeV} \]
"Natural" models are tuned at level: $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 5\%$

$\lambda_h \sim 0.13 \quad \rightarrow \quad g_T = \frac{m_T}{f} \sim 1 \quad (f \gtrsim 600 - 800 \text{ GeV})$

$\mu_h^2 \sim (89 \text{ GeV})^2 \quad \rightarrow \quad f \lesssim 500 \text{ GeV} \quad (\text{"natural"})$

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How “bad” is this tuning?

Other coincidences:

- **Solar eclipse:** ~5%
  (moon/sun diameter and distance from earth)

- **Hadron physics -- dineutron resonance** ~ 5%
  (unbound by amount : \( E_b \sim 100 \text{ keV} \))

- **Proton stability -- quark masses** \( \frac{m_{u,d}}{m_{proton}} \) ~ 0.5%
To reduce tuning can make “natural” models more elaborate:

Supersymmetry
i) Compressed sparticle spectrum; Stealth supersymmetry; R-parity violation
ii) Dirac Gauginos
iii) Color-neutral naturalness (e.g. folded supersymmetry)
   -- color factor of scalar-top comes from hidden QCD

Composite Higgs
i) Twin composite Higgs models
ii) Supersymmetric composite Higgs models...

Typically
\[
\text{tuning} \sim \frac{1}{\text{complexity}}
\]
Is naturalness relevant for Higgs mass?

*example pion mass difference:*

\[
M_{\pi^+}^2 - M_{\pi^0}^2 = \frac{3\alpha}{4\pi} \Lambda^2 \approx (35 \text{ MeV})^2 \quad \Rightarrow \quad \Lambda \lesssim 850 \text{ MeV}
\]

*new physics: rho meson 770 MeV!*

**Higgs mass:**

\[
\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2} \left( 4m_t^2 - 2m_W^2 - m_Z^2 - m_H^2 \right) \Lambda^2 \simeq (125 \text{ GeV})^2
\]

\[
\Rightarrow \quad \Lambda \sim 700 \text{ GeV}
\]

*new physics: ????
Abandon naturalness as a criterion for Higgs mass!

Already failed for the cosmological constant!
-- no new physics (supersymmetry!) at $\sim 10^{-3}$ eV

$$\mathcal{L}_{SM} = \Lambda_{UV}^4 + \Lambda_{UV}^2 H^+ H + \ldots$$

Positive mass dimension terms not determined by naturalness?

Instead, construct **minimal** model with:

- Gauge coupling unification
- Dark matter candidate
- UV completion

**Simple alternative:**

[Wells 2003; Arkani-Hamed, Dimopoulos 2004]

“**Unnatural**” Split SUSY

[ TUNED ]

$(\sim 10^{-4})$

Collider signal: Long-lived gluino!
“Split” Composite Higgs

- Spontaneous symmetry breaking scale \( f \gtrsim 10 \text{ TeV} \) (eliminates bounds from indirect constraints)
- Tuned Higgs potential \( \sim 10^{-4} \)
- Minimal coset: \( \text{SU}(7)/\text{SU}(6) \times \text{U}(1) \) --- doublet \( H \), triplet \( T \) and singlet \( S \)

\[
\begin{align*}
\text{Resonances} & \quad \chi \\
T & \quad \text{color triplet} \\
S & \quad \text{DM} \\
h & \quad t
\end{align*}
\]

Low-energy spectrum: Standard Model + S + T + \( \chi \)
Color triplet decay:

\[ \mathcal{L} \supset \frac{c_3^T}{24\pi^2 f^2} |\lambda_{bc}| |\lambda_{\nu}| |\lambda_{\tau}| S^2(T^c t^c b^c) \]

Dimension-6 term

\[ T \to tbSS \quad \Rightarrow \quad c_T \approx 0.2 \text{ mm} \left( \frac{1}{c_3^T} \right)^2 \left( \frac{8}{g_\rho} \right)^3 \left( \frac{3 \text{ TeV}}{m_T} \right)^5 \left( \frac{f}{10 \text{ TeV}} \right)^4 \]

\( f > 10 \text{ TeV} = \text{long-lived decay} \)

Can produce a displaced vertex!

Sign of unnaturalness!
Nonetheless, a colored superpartner or resonance could still show up at Run 2!

Natural Higgs
\( \sim 125 \text{ GeV} \)

Models are increasingly elaborate and tuned \( \lesssim 5\% \)

Nonetheless, a colored superpartner or resonance could still show up at Run 2!

Unnatural Higgs
\( \sim 125 \text{ GeV} \)

Electroweak scale is meso-tuned \( \sim 10^{-4} - 10^{-6} \)

Long-lived gluino (split SUSY) or color-triplet (split composite Higgs)

Evidence that we live in a Multiverse?
LHC Run II

- LHC will run at 13-14 TeV until end of 2018
- Expect $\sim 100 \text{ fb}^{-1}$ (2015 to date: $\sim 4 \text{ fb}^{-1}$)

STAY TUNED!  [pun intended]