Naturalness in the LHC Era and Beyond

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Naturalness can be described various ways. Most simple-minded:
Dimensional Analysis: dimensional quantities of order largest possibly relevant mass scales

1. $m_H^2 = M_p^2$
2. $\Lambda = M_H^4$
3. $H_I = M_P$ (BICEP: 10^{-4})
4. Neutrino masses, unification scale, fluctuations in inflation,...

In quantum field theory, in general, even if a parameter is small in a zeroth order lagrangian, it will be generated through quantum corrections (problem of “quadratic divergences" for Higgs mass, quartic for cosmological constant.

Natural models for Higgs mass: symmetries can help

$m_H^2 =$ largest mass-squared parameter transforming like m_H^2 under (broken) symmetry

Supersymmetry: rhs supersymmetry breaking parameter.

$$m_H^2 = m_{3/2}^2 \quad m_H^2 = \frac{|F|^2}{M^2}$$

for some appropriate mass scale M.

Natural models: dynamics can help

Technicolor/composite Higgs and variants: above some scale, no parameter in the effective theory corresponding to a Higgs mass. Dimensional analysis:

$$m_H^2 \sim \Lambda^2$$

Model building challenging: flavor, precision electroweak. But scale naturally rather higher.

Naturalness: what is it?

1. Failure of dimensional analysis: why is $m_H \ll M_p$, $m_H \ll M_{L-violation}$, other large physics energy scales.
2. 't Hooft: small parameters should only arise if the theory is more symmetric if they vanish
3. Large radiative corrections to Higgs mass:

$$\delta m_H^2 = \frac{\alpha_W}{4\pi} \Lambda^2_{\rm new\ physics}$$

Here the “new physics" is that responsible for the Higgs particle (more precisely which cuts off the divergence in the Higgs self-energy corrections).

Fine tuning

The large radiative corrections look particularly absurd, if, say, $\Lambda_{\text{new physics}} = M_p$. Says something like

$$m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023$$

$$-36,127,890,984,789,307,394,520,932,878,928,917,398$$

This looks crazy!

A *natural* theory of the Higgs

1. Would yield a Higgs mass consistent with dimensional analysis
2. Implement 't Hooft's notion of naturalness
3. Avoid the absurdity above

Candidates:

1. Technicolor, composite Higgs: $\Lambda_{\rm new\ physics} =$ scale of new strong interactions (RS: "dual" to this)
2. Supersymmetry: $\Lambda_{\rm new\ physics} =$ scale of supersymmetry breaking

In each case, $\Lambda_{\rm new\ physics}\tilde{}{\rm TeV}$.

Idea of Naturalness under stress already before LHC; now much more severe.

SUSY: very concrete models, some successes (unification, dark matter). Naive estimate:

$$m_H^2 \sim m_Z^2 \sim m_{susy}^2$$

So with *TeV* limits on susy particles, naively part in 100 fine tuning. 125 GeV Higgs suggests 10 TeV susy particles $\rightarrow 10^{-4}$ tuning.
Detailed models may do better, but a general worry.

Unnatural Alternatives

1. Landscape plus anthropics (success for cosmological constant)
2. Something else?

Any guidance? How tuned might things be? In first case, can imagine being concrete. Would need to know something about distribution of theories (gauge groups, degrees of freedom, etc.) and parameters. Many possibilities conceivable.

Landscape and Its possible implications for weak scale

We can hope that we will yet find some natural explanation for the dark energy. But its value is so bizarre that perhaps something like Weinberg's proposal is the true answer.

If so, what might this imply for other questions of naturalness?

Extremist View

Plausibly there is some anthropic reason for the Higgs mass to be comparable to what we have now observed (specifically the weak scale – stellar processes, nucleosynthesis).

$\Rightarrow$

Just one light Higgs. No new physics up to extremely high energy scales (scale of r.h. neutrino masses?). Rather bleak prospect.

Moderation: Supersymmetry at Low Scales, but not So Low

Even in a landscape, supersymmetry *might* be favored. But perhaps some level of tuning might be expected. No compelling case, but some possibilities:

1. Approximate low energy supersymmetry might be important to understand the stability of *our* vacuum (recently Greene, Weinberg et al have stressed the severity of the problem; earlier raised by Festuccia, Morisse, M.D. stressed stability automatic if our vacuum is approximately supersymmetric).
2. Within supersymmetric states of a landscape, lower energy supersymmetry might be favored. But there could be counter pressures, e.g. higher energy supersymmetry breaking might be important in understanding inflation.

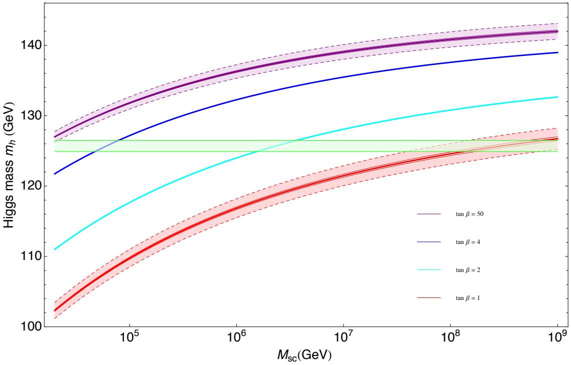
More generally, maybe we are simply too arrogant in the formulation of our fine tuning constraints. Without understanding *where* the laws of nature originate, we have no real understanding of whether things might be tuned, and no idea what constitutes excessive tuning.

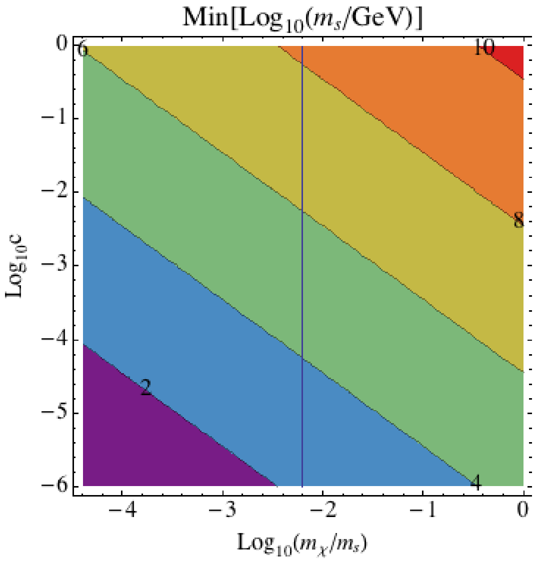
If tuned, by how much?

Different viewpoints.

1. “Mini Split" (Arkani-Hamed et al, Dimopoulos et al): Scale of supersymmetry breaking very high, 1000’s of TeV. Resolves flavor problems of supersymmetry – but perhaps not high enough to explain baryon/lepton number conservation. Naively would expect new physics out of reach for any conceivable accelerator and to intensity frontier experiments. But proponents offer a complicated scenario which might yield observable LHC phenomena (light gauginos). Scale is also rather high for the Higgs mass (proponents restrict tan β).
2. Take the Higgs mass as a clue. For a broad range of tanβ, $10 - 30$ TeV. Another scale pointing to this range: cosmological moduli problem. Lightest states: could be at this scale, or somewhat lower.

From Arkani-Hamed et al:




Min[Log$_{10}$(m_s/GeV)]
6
10
8
2
4
0
−1
−2
−3
−4
−5
−6
Log$_{10}$c
−4
−3
−2
−1
0
Log$_{10}$(m_χ/m_s)

Implications of the High Scale View

1. Most susy states out of reach of LHC. Perhaps gluinos if “anomaly mediated" spectrum.
2. Dark matter might be wimps (winos?), but might well be something else (axions).
3. First evidence for new physics might come in flavor: $\mu \rightarrow e + \gamma$ and d_n, if SUSY in the ten TeV range, would seem likely to appear in the next generation of experiments.