Alternative Futures for Particle Physics

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Energy Frontier Workshop, Brookhaven National Laboratory, 2013

A tension between naturalness and simplicity

The decades prior to July 4, 2012, saw the triumph of every aspect of the Standard Model – strong interactions, electroweak physics, the CKM theory – but left the question of the origin of electroweak symmetry breaking unanswered.

There have been lots of good arguments to expect that some dramatic new phenomena should appear at the TeV scale. But given the exquisite successes of the Model, the *simplest* possibility has always been the appearance of a single Higgs particle, with a mass not much above the LEP exclusions.

In high energy physics, *simple* has a precise meaning: a single Higgs doublet is the minimal set of additional (previously unobserved) degrees of freedom which can account for the elementary particle masses.

A Moment to Celebrate: The Higgs Discovery

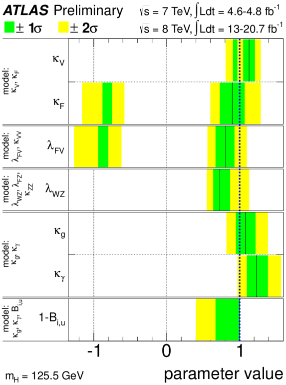
The past year has been extraordinary. The LHC has discovered a scalar particle, probably the Higgs of the simplest version of the Standard Model!

A triumph for experiment! Extremely tough signals: small rates, huge backgrounds.

A triumph for theory: amazing that we can predict production, decay, to such levels of accuracy! All governed by a remarkably simple set of principles. Amazing that one of the most critical signals involves virtual tops. Our understanding of QCD is extraordinary as is our understanding of the electroweak theory.

Summary of coupling results

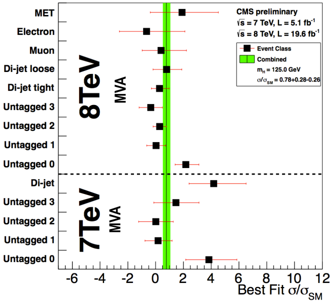
- Overall compatibility with SM: 5-10%
  - No significant deviation from SM
- Note: each model is a different way of fitting the same data
  - correlated, so don't add them up!



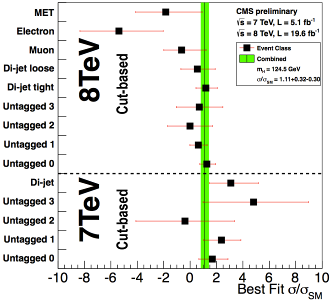
$H \to \gamma\gamma$: Results (channel compatibility)

CMS-HIG-13-001

MVA mass-factorized



Cut-based



7+8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.78^{+0.28}_{-0.26}$

7 TeV: σ/σ_{SM} @ 125.0 GeV = $1.69^{+0.65}_{-0.59}$

8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.55^{+0.29}_{-0.27}$

7+8 TeV:σ/σ_{SM} @ 124.5 GeV = $1.11^{+0.32}_{-0.30}$

7 TeV: σ/σ_{SM} @ 124.5 GeV = $2.27^{+0.80}_{-0.74}$

8 TeV: σ/σ_{SM} @ 124.5 GeV = $0.93^{+0.34}_{-0.32}$

- Despite the same names, the untagged categories in MVA and Cut-basd are not equivalent

Triumph of Effective Field Theory

More precisely, given the LHC exclusion of a vast array of new physics possibilities (beyond the simplest Higgs) up to about 1 TeV, it is possible that there is no new physics up to this scale. In that case, the interactions of a Higgs at 125 GeV are completely fixed, up to terms of order M_H/TeV.

Possible discrepancies in terms of decay rates can be described in terms of higher dimension operators, or require the appearance of new physics close to the Higgs mass.

It is too early to say that the particle at 125 GeV is a perfect fit. The LHC will establish this (or fail to!) at the 10% level, in several decay channels.

An ILC should be able to take this to far higher levels of precision, particularly in fermion decay channels. Sensitive to new physics up to a few TeV.

We have an important long term program of testing the Higgs, starting with our rather crude agreement at the present time, and proceeding to higher and higher levels of precision. In the absence of discovery of new particles at the LHC, any discrepancy will be a crucial clue to the next direction for particle physics.

Particle Physics at a Crossroads

While the Higgs is a triumph, a historically remarkable convergence of theory and experiment, we have many questions, questions to which we thought we would have answers, or at least clues as to answers, by this stage of the LHC program.

Violating Strict Rules

I was always taught: never begin a paper, a slide, with a question, especially if you don't have an answer.

But we are in a situation which cries out to ask difficult questions. So today, almost *every* slide will start with a question.

A List of Questions

While the Higgs is the simplest explanation of particle masses, the Standard Model isn't simple. Most of what seems important in nature could be accomplished with far fewer degrees of freedom. At the same time, the rather bizarre pattern of parameters gives rise to the rich phenomena we see in nature. We also know things about nature which require still more degrees of freedom.

So *simplicity* can't ultimately be a good guide (at least without some other framework).

The Big Questions in Particle Physics

Part of what excites all of us about this field is the big questions we get to ask:

1. What accounts for the particles – degrees of freedom – we observe in nature?
2. What accounts for the parameters of the Standard Model – the masses of elementary particles and their couplings?
3. What is the dark matter?
4. What is the dark energy?
5. What is the physics which underlies inflation?
6. What is the physics which reconciles gravity and quantum mechanics? Does this physics explain the very nature of our universe?

Many of you would list others which you care passionately about. I'd like to focus on a few with direct relevance to the Snowmass process.

1. Is the Higgs all there is? Hierarchy/Dimensional Analysis/Naturalness would say no.
2. Dark Matter: could readily be explained by TeV physics, but there are other compelling possibilities.
3. Dark Energy: my betting is that it is simply a cosmological constant, but its bizarre abundance undermines our most elementary notions of dimensional analysis/naturalness.

Naturnalness: Theorists Dogma or Still an Important Clue?

Most theoretical speculation about Physics Beyond the Standard Model, and especially TeV scale physics, has started with the principle of naturalness.

Technicolor, Supersymmetry, Randall Sundrum, Large Extra Dimensions, Little Higgs.... – all involve problem of constructing natural theories.

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, $\Lambda_{\rm new\ physics} = M_p$. 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, $\Lambda_{\rm new\ physics}$˜TeV.

Supersymmetry: A concrete Realization of Naturalness

It’s clearly an act of arrogance, given our present situation, to claim that one or another of these approaches is best. A skeptic can justifiably argue that they are all likely wrong (there is no prize for being the “least wrong"). But I will focus most of my questions on supersymmetric theories, in part simply because these theories are the most explicit, and solutions to the problems of naturalness, or failures, are easy to describe.

What are the challenges for supersymmetric theories

The hypothesis that low energy supersymmetry is the natural theory which explains the Higgs mass was already under stress at the end of the LEP program, and the Tevatron had also tightened the screws. The problem was twofold.

1. In the simplest version of low energy supersymmetry, the MSSM, the Higgs mass, before including quantum effects, satisfies $m_H < M_Z$. By the end of LEP II, $m_H > 114$ GeV.
2. M_Z is the natural mass scale of the theory; the Tevatron had excluded superpartner masses several times this.

In the minimal model (MSSM), one can be rather explicit about the tuning problem:

$$\delta m_H^2 \approx 12 \frac{y_t^2}{16\pi^2} m_{\tilde{t}}^2 \log(\Lambda/\tilde{m}_t). \qquad (1)$$

This is not as extreme as our previous problem. If $m_{\tilde{t}} = 1$ TeV, we need something like:

$$m_H^2 = 2,465,281 - 2,449,663$$

Not *so* nice, but not as absurd as before.

Might things still be natural?

Things would be better if the stop were lighter. Instead of a fine tuning of a few parts in a thousand, a top squark of 500 GeV, say, would reduce the tuning substantially, especially if the cutoff, Λ (the scale of the "messengers" of supersymmetry breaking) were not too high (gauge mediation).

$$m_H^2 = 146,857 - 131,232$$

Hardly seems tuned at all!

But then why is the Higgs so heavy?

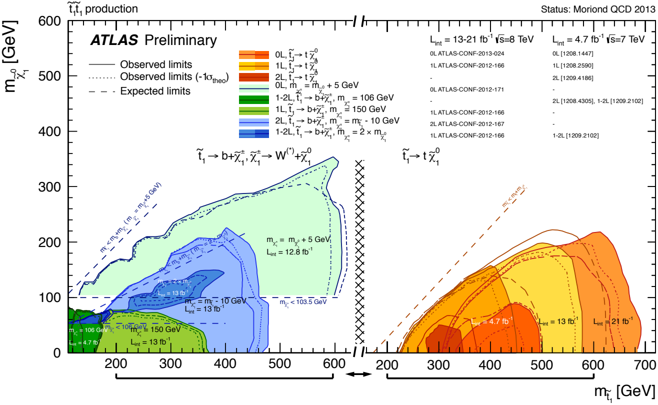
But then another problem: in the MSSM, a Higgs mass of 125 GeV requires that the stop mass be about 10 TeV *or larger*, or that there be large (and tuned) “A Terms". The large stop mass would be 100 times more tuned than previously (alternatively, one can tune the so-called *A* parameter):

$$m_H^2 = 24,498,132 - 24,496,627$$

Naturalness through more degrees of freedom?

One can do better by adding an additional degree of freedom to the Standard Model, a gauge singlet, S. Yields the NMSSM. One can also/alternatively add another gauge symmetry. This allows a larger Higgs self-coupling, and the Higgs can, even before quantum corrections, be somewhat heavier than m_Z. Modest tunings (10 % or so – Ruderman et al).

So the naturalness of supersymmetry, in the strict sense (little or no tuning) hinges on the stop mass. This will be further constrained by LHC.


$\tilde{t}_1\tilde{t}_1$ production
Status: Moriond QCD 2013
ATLAS Preliminary
Observed limits
Observed limits ($-1\sigma_{theo}$)
Expected limits
0L, $\tilde{t}_1 \to t\tilde{\chi}^0_1$
1L, $\tilde{t}_1 \to t\tilde{\chi}^0_1$
2L, $\tilde{t}_1 \to t\tilde{\chi}^0_1$
0L, $m_{\tilde{\chi}^\pm_1} = m_{\tilde{\chi}^0_1} + 5$ GeV
1-2L, $\tilde{t}_1 \to b+\tilde{\chi}^\pm_1$, $m_{\tilde{\chi}^\pm_1} = 106$ GeV
1L, $\tilde{t}_1 \to b+\tilde{\chi}^\pm_1$, $m_{\tilde{\chi}^\pm_1} = 150$ GeV
2L, $\tilde{t}_1 \to b+\tilde{\chi}^\pm_1$, $m_{\tilde{\chi}^\pm_1} = m_{\tilde{t}_1} - 10$ GeV
1-2L, $\tilde{t}_1 \to b+\tilde{\chi}^\pm_1$, $m_{\tilde{\chi}^\pm_1} = 2 \times m_{\tilde{\chi}^0_1}$
L_{int} = 13-21 fb^{-1} $\sqrt{s}$=8 TeV
0L ATLAS-CONF-2013-024
1L ATLAS-CONF-2012-166
-
0L ATLAS-CONF-2012-171
-
1L ATLAS-CONF-2012-166
2L ATLAS-CONF-2012-167
1L ATLAS-CONF-2012-166
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
-
2L [1208.4305], 1-2L [1209.2102]
-
-
1-2L [1209.2102]
$\tilde{t}_1 \to b+\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1 \to W^{(*)}+\tilde{\chi}^0_1$
$\tilde{t}_1 \to t\tilde{\chi}^0_1$
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}^\pm_1}$ ($m_{\tilde{\chi}^\pm_1} = m_{\tilde{\chi}^0_1} + 5$ GeV)
$m_{\tilde{\chi}^\pm_1} = m_{\tilde{\chi}^0_1} + 5$ GeV
L_{int} = 12.8 fb^{-1}
$m_{\tilde{\chi}^\pm_1} = 2 \times m_{\tilde{\chi}^0_1}$
L_{int} = 13 fb^{-1}
$m_{\tilde{\chi}^\pm_1} = m_{\tilde{t}_1} - 10$ GeV
L_{int} = 13 fb^{-1}
$m_{\tilde{\chi}^\pm_1} < 103.5$ GeV
$m_{\tilde{\chi}^\pm_1} = 106$ GeV
L_{int} = 4.7 fb^{-1}
$m_{\tilde{\chi}^\pm_1} < 106$ GeV
$m_{\tilde{\chi}^\pm_1} = 150$ GeV
L_{int} = 13 fb^{-1}
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}^0_1}$
L_{int} = 4.7 fb^{-1}
L_{int} = 13 fb^{-1}
L_{int} = 21 fb^{-1}
$m_{\tilde{\chi}^0_1}$ [GeV]
600
500
400
300
200
100
0
200
300
400
500
600
200
300
400
500
600
700
$m_{\tilde{t}_1}$ [GeV]

Naturalness through evading bounds: R-Parity Violation

The bounds on supersymmetric particles are weakened if R parity is not preserved. For example, if the low energy theory includes the operator

$$\delta W = \bar{u}_3 \bar{d}_3 \bar{d}_2 \tag{2}$$

then baryon (and lepton) violation can occur at acceptable levels, and the principle signal of supersymmetry is no longer missing energy (Grossman et al, others). It is still necessary to introduce additional degrees of freedom if one is to obtain a 125 GeV Higgs without tuning.

Has implications for other questions: dark matter, dark energy, baryogenesis, flavor

Discovering evidence of supersymmetry, and these additional degrees of freedom, would be extremely exciting.

New symmetry of nature, new particles, new dynamics, *orthodox* ideas of naturalness will be vindicated.

More generally, *any* discovery of degrees of freedom beyond that of the simplest Standard Model will be revolutionary.

Particle physics will have a clearcut program of elucidating these new phenomenon for many years.

The happiest outcome.

How Natural Should Things Be?

But many of us are a bit uneasy. First, the NMSSM is more complicated than the simplest models (simplicity principle? – at least MSSM is simplest structure allowed by basic principles), and must lie in special regions of parameter space . The exclusions of the stop are getting stronger.

Alternatively, could it be that things are tuned by a little? A lot?

We've seen examples of various hypothetical degrees of tuning, from modest to absurd. How much is plausible?

Various criterion have been used for measuring tuning, and various declarations of what is “acceptable" (to whom??). All somewhat arbitrary. Force us to ask: why?

Early ideas: complex theory at microscopic level. Simple low energy emergent theory; some notion of universality.

The qualitative features of the world around us shouldn’t be contingent on very precise details of microscopic theory, but not a terribly sharp notion. More recently landscape hypothesis makes more well-defined.

A much bigger naturalness problem: Dark energy (cosmological constant)

The fine tuning of the dark energy is so severe that it passes my latex skills to illustrate. Naively part in 10^{120}. Already in early days of supersymmetry (1982!), it was realized that if one didn't have a natural explanation of this question, ideas for naturalness of weak interactions were on shaky foundation.

Indeed, we still have no natural explanation!

Weinberg's proposal for the cosmological constant

A landscape of vacua. If vastly more than 10^{120}, and if c.c. randomly distributed, only those for which the cc is comparable to what we observe can support stars, galaxies (observers?).

The best proposal we have.

Successful *prediction* of the dark energy.

Aside: A Question for the Cosmic Frontier

Simplest explanation for the dark energy: cosmological constant.

Quintessence: dark energy associated with an *extremely* light field. Hope initially was that such a field could explain why the peculiar value of the dark energy *now*, but not the case. Far more tuned than c.c. No anthropic rationale.

Analogy with fact that Higgs mass is surprising, but its interactions are not (e.g. not accompanied by other light particles with peculiar properties).

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.

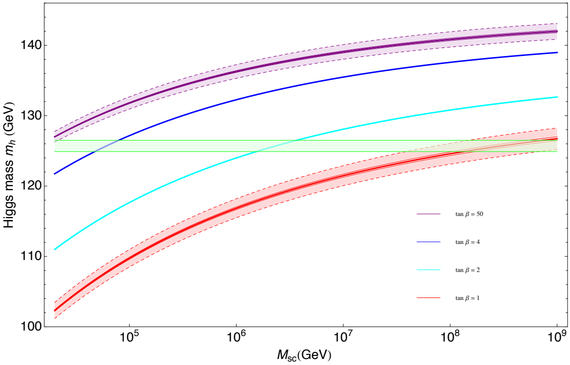
More generally, maybe we are simply too arrogant in the formulation of our fine tuning constraints. Without understanding *where* the laws of nature originate, we have no real understanding of whether things might be tuned, and no idea what constitutes excessive tuning.

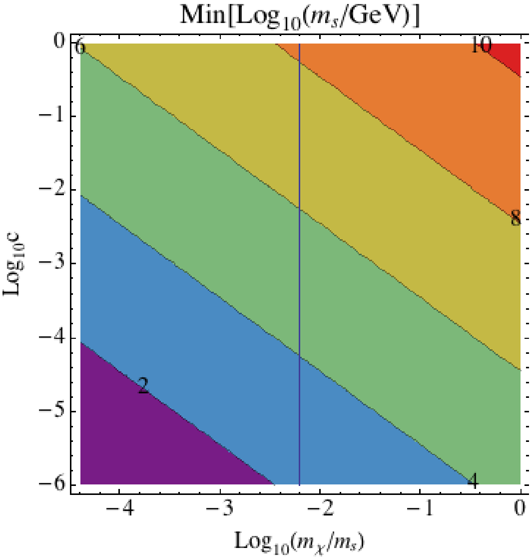
If tuned, by how much?

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

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.

An exciting and Remarkable Present

1. Exquisite understanding of the laws of nature. Higgs discovery and measurement of its production and decay the culmination of five decades of study of the Standard Model. Triumph for the *principle of simplicity*.
2. ILC: perhaps the tool to clinch (or not!) this story. Precision studies of the Higgs.

Alternative futures

1. Naturalness triumphs – new physics discoveries at 14 TeV.
2. Naturalnesss fails a little bit: Higgs clue to the next important nervy scales.
    1. Split supersymmetry: LHC discovery of light gluino
    2. Unsplit – Intensity frontier provides evidence for a new scale at 10's of TeV ($\mu \rightarrow e + \gamma$; d_n). *Eventually* able to probe this scale.
3. Big failure of naturalness