Naturalness Under Stress: SUSY after 5 fb^{-1}

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My Charge

Michael Peskin wrote to me in October, saying “So, for this talk, it would be good to have a lofty theoretical perspective to get people thinking about the whole range of possibilities. "

Lofty is intimidating. Especially at this critical time (the 5 fb^{-1} moment in the LHC program). It is clear that a lot of my thinking through the years about BSM physics in general and SUSY in particular has been, at best, off the mark.

Two major components: *naturalness* and *genericity*.
Both of these now look questionable. Simple-minded, “generic" approaches appear tuned; less tuned constructions are not obviously generic.

So I come as a penitent. My goal is to try to examine the assumptions which the community – and I – have been making. I will argue that some were always questionable. I hope some of this “soul searching" will help point some of us in some productive, new directions. Some of the arguments will be bottom up, some top down.

Outline

1. Naturalness is under tension – supersymmetry, the Higgs mass.
2. Rethinking naturalness and genericity.
3. Status of dynamical supersymmetry breaking.
4. What if Standard Model-like Higgs between $115 - 130$ GeV?
5. What if no standard model-like Higgs below 600 GeV?

We already confront a susy scale in the $\mathrm{TeV} \gg M_Z$ energy range.

Possibly within two weeks and almost certainly within a year, we will confront either:

1. Higgs with mass high compared with susy expectations.
2. No standard model-like Higgs below 400 GeV.

Of course, if we have an interesting missing energy signal with jets or leptons – we all know what we will be doing.

Some people are happy

In September, I attended the conference "Lattice Confronts Experiment" at Fermilab. There, results were reviewed which suggest that, at an 80% confidence level, the Standard Model Higgs is excluded already by Tevatron data. As most of the conference participants were technicolor enthusiasts, there was an almost celebratory atmosphere (No SUSY! No light Higgs!).

Much of the discussion on these topics was devoted to “walking", trying to resolve the problems of flavor and precision electroweak. But it was acknowledged that technicolor faces additional serious challenges from flavor and especially understanding the top quark.

A general lesson: *if* new strong interactions are responsible for electroweak symmetry breaking, they must have *very special* properties. Very special numbers of techniquarks, special gauge structure... They are not generic. This same theme should now be central to our thinking about supersymmetry, or any new Beyond the Standard Model (BSM) physics.

Some further surprising views on the situation

Last summer, I attended the String Phenomenology and SUSY conferences. At the string phenomenology conference, two statements surprised me, reflecting a surprising optimism:

1. Repeated talks opening with the assertion that “The Goal of String Phenomenology is to Derive the MSSM from String Theory".
2. Assertion by Gordy Kane and collaborators that the susy breaking scale should be 10’s of TeV (moduli problem), and as a result, the discovery of a 130 GeV Higgs, *and nothing else* (or possibly light gluinos) *would be a triumph for string theory.*

While it may not be quite time to bury the MSSM, one of my principal themes will be that if there is low energy supersymmetry, it is probably doesn't fit within the various generic ideas we have been studying the last (three) decades.

For somewhat different reasons than Gordy, I am willing to contemplate the (rather disturbing possibility) that there might be modest hierarchies. Perhaps the question is, "If there is a little hierarchy, just how little (or big) is it?".

Sources of Pessimism – and Optimism

Already with the end of the LEP program, there were serious reasons for skepticism about supersymmetry The most natural scale for low energy supersymmetry would seem to be M_Z. The absence of any direct signal, the failure to discover the Higgs, the problem of CP violation, the absence of deviations from the Standard Model in $b \rightarrow s + \gamma$, the non-observation of proton decay, all suggested that supersymmetry, if present, was working hard to hide itself.

The absence of a natural explanation for the observed dark energy, and the emergence of the landscape as a plausible concept, sharpened these concerns.

In the last year, thes concerns have been sharpened. The LHC has quickly excluded broad swaths of the SUSY parameter space; near TeV limits are common.

As Michael Peskin said in Mumbai, “No reasonable person could view [the SUSY exclusions] without concluding that we need to change our perspective." He added the question: “What new perspective is called for?"

I am certainly no wiser than Michael, so I won’t claim to have any answer he doesn’t. But I hope to provide some guidance for thinking about these issues.

Naturalness: three logical possibilities

Assuming that supersymmetry exists at some scale well below the Planck scale:

1. Conventional ideas are correct. Within some class of models, the weak scale arises without appreciable fine tuning of parameters.
2. There is some modest level of fine tuning. We will discover – or just fail to discover – supersymmetry, more or less in some form we imagined, with fine tuning of, say, a part in 1000.
3. There is lots of tuning. We will see a relatively light Higgs. Nothing else.

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What is naturalness? Should we believe in it?

Why would we doubt?

Hierarchies in nature for which we have possible symmetry or dynamical explanations:

1. Weak/Planck hierarchy
2. Yukawa hierarchies

Hierarchies for which we don't:

1. The cosmological constant (huge elephant) (part in $10^{68} - 10^{120}$).
2. Inflation (part in 100?)
3. Hypothetical: $\theta_{qcd} \rightarrow \text{ axion} - f_a/M_p$
4. Hypothetical: dark matter (see (3), or new light state tuned for thermal production).

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All of these problems are substantially ameliorated by supersymmetry, but the first two are not resolved in any framework I know.

So logically we have to acknowledge, even before proposing an underlying explanation for these puzzles, that in imposing notions of naturalness we are on shaky grounds.

SUSY, of course, has other attractive features:

1. Unification
2. Dark matter

I will try to convince you that there are more.

The Landscape As a Setting for Questions of Naturalness

The *landscape* has been the Damocles sword hanging over our (SUSY's) head. It is, for better or worse, the most compelling explanation we have of the observed dark energy.

Without worrying how the landscape comes about, can embody the basic idea in the statement:

The laws of nature we observe (degrees of freedom, lagrangian parameters) are selected from a large ensemble of possibilities.

The probability distribution associated with this ensemble depends on the underlying microphysics (string theory? some larger structure incorporating gravity?), cosmology, other unknown features.

Model Building in a Landscape Setting

From this perspective, a *model* is a choice of probability distribution for d.o.f, symmetries, parameters. In making a selection from the distribution, we impose certain prior constraints; these may be anthropic (as in the prediction of the dark energy) or simply viewed as observational. Predictions arise if some outcome is strongly favored.

Models can fail! [“Falsifiable"]

Within such a framework, *naturalness is a precise notion*. We can ask the relative likelihood, say, of a light Higgs given supersymmetry or not.

Question of low energy susy is, then, how common, in the landscape, is dynamical susy breaking, vs. non-dynamical or total absence of supersymmetry.

The answer to this question is not known within, e.g., any well-understood string model.

Models and Their Implications for Low Energy Supersymmetry

Model A No SUSY below Planck scale (would seem generic). Low Higgs mass selected by anthropic criteria.

Model B: Assume (motivated by studies of IIB flux vacua) non-dynamical breaking of supersymmetry, superpotential parameters distributed uniformly as complex numbers: high (Planck) scale susy favored even by small Higgs mass, cosmological constant. (Douglas/Susskind)

Model C: Dynamical breaking favors lower breaking of SUSY (Gorbatov, Thomas, M.D.).

Model D: Dynamical breaking and discrete *R* symmetries: very low scales (as in gauge mediation).

So in landscape, question of low energy susy is one of relative probability of dynamical susy vs. non-susy or non-dynamical susy.

Not enough known about landscapes from any underlying theory to settle these questions from “top down".

A cosmological argument for low scale susy in the landscape:

One attempt at a “top down" argument:
The prototypical flux landscape models generate a large class of effective actions, and one counts vacua by counting stationary points. Typically these will be non-supersymmetric or exhibit large supersymmetry breaking. But a typical low cosmological constant state found this way will have *many* neighbors with negative cosmological constant. Typically decay will be very rapid.

Large volume, weak coupling typically are not sufficient to account for generic stability. But Supersymmetry is!

For a broad class of models (Festuccia, Morisse, M.D.):

$$\Gamma \propto e^{-2\pi^2\left(\frac{M_p^2}{m_{3/2}^2}\right)} \tag{1}$$

A related question: Does one expect symmetries (pointing to low scale breaking, as needed to suppress proton decay, etc.?). Naive landscape counting in flux models: no! Only an exponentially small fraction of fluxes allow symmetry (Z. Sun, M.D.).

Challenges accepted wisdom that symmetries are natural.

But perhaps *too* naive. (Festuccia, Morisse, M.D.)

A Little Hierarchy?

In such a framework, notions of naturalness, we see, can hold. If there is low energy susy, might one still encounter a little hierarchy, or do strict notions of naturalness hold?

E.g. inflation, with SUSY, typically requires $1/100$ fine tuning. Without SUSY generally *much* more severe. If the dynamics of inflation are tied to those of supersymmetry breaking, there might be a tension between the two (higher scales more natural for inflation, lower scales for Higgs mass). The result could be a “compromise". Dark matter might also lead to such a tension.

Models relating supersymmetry to inflation can give little or “medium size" hierarchies.

Dynamical Breaking of Supersymmetry: A Status Report

These arguments suggest that any truly natural implementation of supersymmetry is necessarily dynamical. There has been much progress in recent years in understanding dynamical supersymmetry breaking, due to the realization that *metastable supersymmetry breaking* is likely central (ISS, others).

Simplest models: “retrofitted".

Metastable O'Raifeartaigh Models

Simple OR model:

$$W = X(\lambda A^2 - f) + mAY \tag{2}$$

As required by theory of Nelson and Seiberg, model possesses a continuous R symmetry:

$$X \to e^{2i\alpha} X \quad Y \to e^{2i\alpha} Y \quad A \to A \qquad \theta \to e^{i\alpha}\theta. \tag{3}$$

We don't expect (exact) continuous global symmetries in nature, but discrete symmetries are more plausible. Take a discrete subgroup of the R symmetry, e.g. $\alpha = 2\pi/N$.

Allows

$$W = X(\lambda A^2 - f) + mAY + \frac{X^{N+1}}{M_p^{N-2}} + \dots \qquad (4)$$

(M could be smaller than M_p).

SUSY minimum for large X; metastable minimum near the origin. At low energies the last term is irrelevant, so in this model, the continuous R symmetry is approximate, an accidental consequence of the discrete symmetries.

Retrofitting the O'Raifeartaigh Models

Gaugino condensation a crucial element in understanding of SUSY dynamics.

Essence: $\langle\lambda\lambda\rangle$ breaks a discrete *R* symmetry, mass gap (dimensional transmutation). Order parameter dimension three.

This can be generalized to models with order parameters of dimension one: *S*.

Retrofitting O'Raifeartaigh Models

Now we can take the earlier OR model and make the replacements:

$$W = W = X(\lambda A^2 - f) + mAY \Rightarrow X(\lambda A^2 - \frac{\langle\lambda\lambda\rangle}{M_p}) + \kappa\, S\, AY \quad (5)$$

1. All scales dynamical
2. Model is natural (structure enforced by discrete symmetries)
3. $< W >$ of correct order to cancel cosmological constant (still need to tune):

$$\langle W \rangle \sim f M_p \quad (6)$$

Model building

1. (Approximate) R symmetry breaking: retrofit models of Shih which spontaneously break the *R* symmetry.
2. Mediation – gravity mediation straightforward. Gauge mediation: several strategies to introduce messengers.
3. μ term: Retrofit as well: $\lambda S H_U H_D$. $< F_S > \ll S^2 \Rightarrow$ Small B_μ, large $\tan\beta$.
4. Scale of susy breaking: many possibilities.

A rich space of models to explore.

Higgs Mass and Low Energy Supersymmetry

Absence of SUSY signals to date: simplest, generic models of low energy susy are highly tuned.

Standard Model Higgs discovery or exclusion: SUSY right around the corner?

We may know something in the next few days; certainly over the next few months. Either result will sharpen our thinking about the scale of SUSY.

Higgs discovery

Much has been said about the problem in the MSSM. A Higgs of, say, 125 GeV requires a large stop mass and/or large *A* terms. This view points to a high susy breaking scale and significant tuning. Consistent with our "modest hierarchy" viewpoint.

NMSSM: usually considered as a model to generate a μ term. But, e.g., thinking about retrofitting, no reason not to include μ, mass for singlet. Large masses for Higgs can be natural (Seiberg, Thomas, M.D.; Ross, Schmidt-Holberg,; Banks). SUSY scale might be just within reach.

Other *natural* possibilities?

Higgs Exclusion

Could be triumph of strong EWSB, but precision electroweak suggests new, light degrees of freedom. *No longer just making excuses for absence of SUSY but for Higgs itself .*

Accounting for this: light stops, large *A* terms? Other frameworks?

Light stops: potential for improving tuning. Strict naturalness? SUSY around the corner?

So SUSY at the LHC?

From first 5 fb^{-1}, it seems our simple-minded ideas about the MSSM – either within gravity or gauge mediation – are probably not right.

1. Natural implementations of EWSB supersymmetry are likely to involve special features – light stops, generalized NMSSM, something else...
2. EWSB might be a little bit unnatural – some modest hierarchy. SUSY then may or may not be within reach
3. EWSB might be totally unnatural, with no relic of low energy supersymmetry.

Higgs discovery or not will provide focus for our thinking, but won't settle by itself which possibility is realized.

At the same time, the theoretical arguments for low energy supersymmetry seem sharper than ever. We have a better understanding of dynamics; a framework in which to set our discussions of naturalness.

The next few months will be very exciting.