SUSY, Landscape and the Higgs

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A tension between naturalness and simplicity

There have been lots of good arguments to expect that some dramatic new phenomena should appear at the TeV scale to account for electroweak symmetry breaking. 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 Quantum Field Theory, *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.

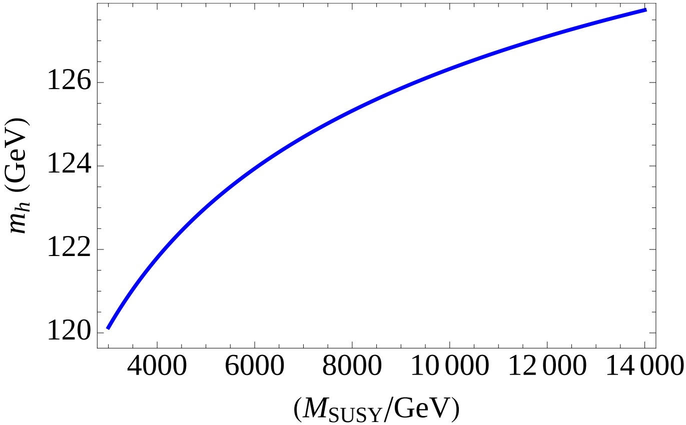
Higgs Discovery; LHC Exclusions

So far, simplicity appears to be winning. Single light higgs, with couplings which seem consistent with the minimal Standard Model. Exclusion of a variety of new phenomena; supersymmetry ruled out into the TeV range over much of the parameter space. Tunings at the part in $100 - 1000$ level.

Most other ideas (technicolor, composite Higgs,...) in comparable or more severe trouble. At least an elementary Higgs is an expectation of supersymmetry. But in MSSM, requires a large mass for stops.

Top quark/squark loop corrections to observed physical Higgs mass ($A \approx 0$; $\tan\beta > 20$)

In MSSM, without additional degrees of freedom:



$$\delta m_H^2 = -\frac{6 y_t^2}{16\pi^2} \tilde{m}_t^2 \log(\Lambda^2 / m_{susy}^2)$$

So if 8 TeV, correction to Higgs mass-squred parameter in effective action easily 1000 times the observed Higgs mass-squared.

Physics in Crisis?

Neil Turok, in a speech (2013) at Perimeter Institute, reported in *Physics World*::

Turok referred to a “very deep crisis in physics" that he believes the field has entered. The problem, according to Turok, is that experiments such as those at the Large Hadron Collider at CERN and the European Space Agency’s Planck space mission have so far failed to find any significant evidence for physics beyond the Standard Model. Turok also told his audience that “There’ve been grand unified models, there’ve been super-symmetric models, super-string models, loop quantum-gravity modells.. Well, nature turns out to be simpler than all of these models." With regard to string theory, Turok said “It’s the ultimate catastrophe: that theoretical physics has led to this crazy situation where the physicists are utterly confused and seem not to have any predictions at all."

He concludes: “But given that everything turned out to be very simple, yet extremely puzzling – puzzling in its simplicity – it’s just perfect for what Perimeter’s here to do. We have to get people to try to find the new principles that will explain the simplicity."

One of our organizers, of course, has addressed this crisis recently in *Scientific American*.

There are three logical possibilities:

1. Nature is *natural*. We are on the brink of significant discoveries
2. Nature is somewhat tuned for a variety of possible reasons (I will mention a few). Higgs mass understood in terms of supersymmetry (say) at 10's to 100's of TeV. We might hope to see deviations in precision measurements, rare processes; perhaps evidence for new physics at much higher energies.
3. Nature is extremely tuned. We won't see new physics at accelerators of the highest conceivable energies.

Natural Supersymmetry

Being tightly squeezed. Requires light stops. NMSSM or other type structure to account for Higgs mass. Appears at least somewhat tuned if true. Problem is that gluino limits are quite strong, and majorana gluino mass (of order 1.4 TeV) feeds into stop. Typically leads to few percent fine tuning.

But perhaps our ideas for realization of supersymmetry not quite right. Models which are not tuned, or only very slightly. An exciting possibility. Could yet emerge in future LHC runs.

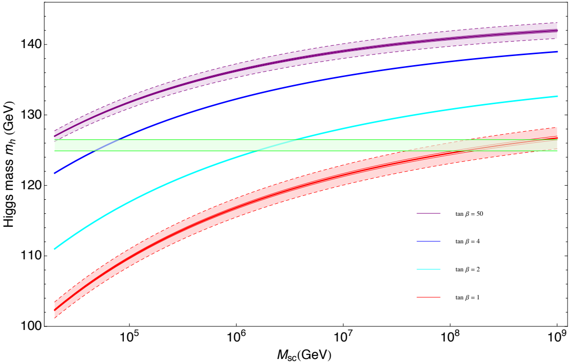
Discovering evidence of supersymmetry (or compositeness, warping...), and these additional degrees of freedom, would be extremely exciting.

New symmetry(yes) of nature, new particles, new dynamics, *orthodox* ideas of naturalness will be vindicated.
We'd have a clear long term program. The happiest outcome!

Slightly Tuned Supersymmetry

For moderate to large tan β, stop masses of order $10 - 100$ TeV can account for the observed Higgs mass. Tuning at part in 10^4 level.

From Arkani-Hamed et al:



(“Mini") Split Supersymmetry

Split supersymmetry: one popular proposal.

1. Starts from argument that gauginos are naturally light compared to scalars
2. Argue that if breaking scale of order 10^4 TeV, flavor problems of supersymmetric theories solved.
3. Small tan β (somewhat tuned) then consistent with observed m_H.

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.

But a price:

Supersymmetry has (often) several features which are quite appealing:

1. Solution of hierarchy problem: cancellation of quadratic divergences.
2. Solution of hierarchy problem: dynamical supersymmetry breaking as origin of hierarchy $m_{3/2} = Me^{-\frac{8\pi^2}{bg^2}}$
3. Coupling constant unification
4. Natural dark matter candidates

In any case, clearly need to reassess what we have thought to be a guiding principle.

Landscape as a Model for Questions of Naturalness

Landscape models have many limitations. But they have the virtue that they make sharp questions of naturalness. [Otherwise, what are we worried about? We don't want the entity responsible for the laws of nature to have to work too hard?] Well defined notion of measure on the space of theories. Impose priors (anthropics? just existing data?). With sufficient understanding, could decide, e.g., low energy susy more or less likely.


TIM LEATHERBARROW
"...HAWKINGS!... I WANT A WORD, WHEN IVE FINISHED JUGGLING THE UNIVERSE!"

Feynman, as quoted by the novelist Herman Wouk:

“It doesn’t seem to me that this fantastically marvellous universe, this tremendous range of time and space and different kinds of animals, and all the different planets, and all these atoms with all their motions, and so on, all this complicated thing can merely be a stage so that God can watch human beings struggle for good and evil - which is the view that religion has. The stage is too big for the drama."

I invite you to think what this implies for fine tuning, anthropics.

Branches of the Landscape

Studies of landscape models (e.g. Type II flux vacua–Douglas, Denef; Dine,Gorbatov,Thomas, Sun) suggest existence of branches with

1. No supersymmetry, just Higgs [for now will not consider technicolor, warping, etc.]
2. Approximate supersymmetry, breaking non-dynamical
3. Supersymmetry, dynamical breaking, no (discrete) R symmetries
4. Supersymmetry, dynamical breaking, discrete R symmetries.

What might favor one or another? We might impose as priors (anthropics?) the value of the cc and the scale of electroweak breaking. Simplest assumption is that most likely is the branch with the largest number of states consistent with these requirements.

Branch Populations and Distributions

The relative numbers of states on each branch is not known. On the non-supersymmetric branch, we would expect that, of states satisfying the cc constraint, one in m_H^2/M_p^2 satisfies the electroweak constraint.

On branches 2-4, however, we can address the question of the scale of supersymmetry breaking.

Scales of Supersymmetry Breaking

Douglas and Denef (also Kachru et al), in simple cases, find superpotential parameters uniformly distributed as complex numbers.

$$\int_{|z|<\epsilon} d^2 z = 2\pi\epsilon^2$$

Non-Dynamical Breaking

Thee crucial (complex) parameters:

1. F_X
2. W_0
3. μ

Price of small susy breaking:

1. $|F_X|^2|W_0|^2|\mu|^2 \sim \left(\frac{m_{3/2}}{M_p}\right)^6$
2. Cosmological constant cancellation: $\frac{\Lambda_0}{|F_X|^2} = \frac{\Lambda_0}{m_{3/2}^2}$

So far simpler to just tune Higgs mass than lower $m_{3/2}$.

Branch 3: Dynamical Susy Breaking

Here $F_X \propto e^{-\frac{8\pi^2}{bg^2}}$ with g^2 distributed uniformly. Price of small susy breaking:

1. $|W_0|^2|\mu|^2 \sim \left(\frac{m_{3/2}}{M_p}\right)^4$
2. Cosmological constant cancellation: $\frac{\Lambda_0}{|F_X|^2} = \frac{\Lambda_0}{m_{3/2}^2}$

High scale breaking still favored.

If μ also generated dynamically, then scales equally likely (decade by decade).

Branch 4: Dynamical SUSY and R Symmetry Breaking

$W, \mu \propto e^{-\frac{8\pi^2}{bg^2}}$

No price for low scale of susy breaking, and tuning of cosmological constant is easier (as previously) with smaller $m_{3/2}$. Now small SUSY breaking is favored.

Lower scales: $= \frac{\Lambda_0}{m_{3/2}^2}$

A priori arguments for the different branches?

How populated? Counting/cosmology?

Might think that (approximate) SUSY states special, rare. More shortly.

Simple considerations for flux vacua suggest that states with symmetries are rare.

Branch 4: Landscape and Symmetries

Naive landscape counting in flux models: states exhibiting symmetries are rare!

Loosely, if N types of fluxes, taking m values, m^N states (say 10^{500}).

Typically only a fraction (say 1/3) invariant under symmetries. so $m^{N/3}$ symmetric states.

So 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.)
Cosmological considerations *might* favor symmetries.

Population of the Different Branches

We have argued that discrete symmetries are likely rare. But what about supersymmetry vs. not.

(Meta) Stability: Most landscape counting: search for stationary points of some (supergravity) potential.

Classical stability: Naively, if N fields (moduli), $\frac{1}{2}^N$ are local minima.
In fact, in particular examples, suppression is more severe (McAlister, Marsh, Wrase): Supergravity plus random matrix theory:

$$P = e^{-0.3N^{1.5}}$$

Quantum stability (tunneling). Naive argument: each vacuum surrounded by a large number of negative cc states (order $\mathrm{several}^N$). Tunneling amplitude to every one must be small.

Greene, Weinberg, more extreme suppression problem in a simple model.

N fields, ϕ_i. Random potential:

$$V = \lambda \left(\sum_i A_{ii}\phi_i^2 v^2 + \sum_{ijk} A_{ijk}\phi_i\phi_j\phi_k v + A_{ijkl}\phi_i\phi_j\phi_k\phi_\ell \right).$$

Fraction of states with tunneling exponent greater than $\hat\beta$ is

$$P(\hat\beta) \approx e^{-\beta N^3 \hat\beta}$$

where $\beta \approx 10^{-3}$.

What features of a particular candidate ground state might account for stability in some generic way?

Small coupling (string coupling), large volume: don't help significantly.

But Supersymmetry!

With exact supersymmetry in flat space, the vacuum is stable. This can be understood as a consequence of the existence of global supercharges, obeying the familiar algebra:

$$\{Q_\alpha, \bar{Q}_{\dot{\beta}}\} = 2P^\mu (\sigma_\mu)_{\alpha\dot{\beta}} \tag{1}$$

With (slightly) broken supersymmetry, expect still true or suppressed. Generally true.

For a broad class of models (Festuccia, Morisse, M.D.), one has a general formula:

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

While hardly a proof, these observations suggest:

Branch 3 with dynamical supersymmetry breaking but no R symmetry may be the most promising. Scale of susy breaking not fixed by considerations of cc and fine tuning of the Higgs mass.

Higgs mass and susy exclusions consistent with our argument against branch 4 (R symmetries, dynamical generation of $\langle W \rangle$.

A priori arguments for the scale of supersymmetry breaking:

1. Nomura, Shirai: Split spectrum assumed generic; wino dark matter at about 3 TeV fixes scale (squarks, leptons more massive by $\frac{\alpha}{\pi}$ factors). μ anthropic (rather than symmetries/dynamics as above).
2. Arkani-Hamed et al: split supersymmetry, $m_{3/2} \sim 10^4$ TeV to avoid FCNC's. Also wino dark matter.

Here we develop an alternative viewpoint.

Moduli as controlling feature of supersymmetry phenomenology/cosmology

Typical of string models. If present, dominate early universe. Successful cosmology requires they reheat the universe, when decay, to temperatures above nucleosynthesis temperatures. Only if *much* higher is conventional picture of thermal dark matter operative.

Requires moduli masses of order 10's of TeV. (Banks, Kaplan, Nelson; Ibanez et al)

Despite some assertions to the contrary, moduli decays themselves usually produce too much dark matter. So perhaps abandon split susy picture (not so obviously generic, in any case) and suppose moduli lighter than the LSP, or R parity violated.

Moduli as Controlling Element in Realization of Supersymmetry

[M. Bose, P. Draper, M.D.]
Can consider (at least) three possibilities:

1. No moduli
2. Supersymmetric moduli (moduli with small F terms, as in KKLT)
3. Non-supersymmetric moduli

Which of these three is realized controls realization of supersymmetry, critical features of cosmology.

No moduli

Conventional cosmology possible. Universe was once very hot. No additional constraints on scale of supersymmetry breaking.

But: unless supersymmetry broken at very high scales, no axion (and understanding axion challenging without supersymmetry).

Supersymmetric moduli: Still no axion. Moduli can be quite heavy. Readily decay to particles and superpartners.

Aside: A Theorem About Decay Rates in Supersymmetric Theories

With unbroken supersymmetry, can often prove exact statements about decay of particles (moduli scalars in this case) to pairs of particles, superpartners. Follows from supersymmetric ward identities. Ex:

$$W = \frac{1}{2} M \Phi^2 + \lambda \Phi \phi \phi. \tag{3}$$

Supersymmetry relates the Green's functions:

$$\langle F_\Phi^*(x_1)\psi_\alpha(x_2)\psi_\beta(x_3)\rangle\epsilon^{\alpha\beta} = 2\langle \Phi(x_1)^*\partial_\mu\phi(x_2)\partial^\mu\phi(x_3)\rangle \; . \tag{4}$$

E.g. from

$$\langle \Phi^*(x_1,\theta_1)\phi(x_2,\theta_2)\phi(x_3,\theta_3)\rangle \tag{5}$$

The left hand side of the Ward i.d. is the coefficient of $\bar\theta_1^2\theta_2\theta_3$ in this Green's function; translating by θ_1 in superspace, the coefficient of this term is the right-hand side of the equation.

To extract the decay amplitudes, we can apply the LSZ formalism. First we note the relations for the Green's functions, in momentum space,

$$\langle F^\dagger F \rangle = p^2 \langle \phi^\dagger \phi \rangle. \tag{6}$$

So we can relate the single particle matrix elements needed for LSZ; those of ϕ and F differ by a factor of m^2, the physical on-shell mass. There are two possible initial states (which can be thought of as the scalar and its antiparticle) and two possible final states in either the two boson or two fermion channel. Combining the Ward identity for the Green's functions and the result for the single particle matrix elements demonstrates the equality of the two boson and two fermion matrix elements. The result is readily verified at tree level.

Similarly, for a scalar coupled to W_α^2, one can prove an equality for the matrix elements (and hence the rates) for the decays: $\phi \rightarrow A_\mu + A_\mu$ and $\phi \rightarrow \lambda\lambda$. When supersymmetry is broken these equalities will fail, but, except for tuned values of the parameters, we expect the rates to be comparable.

Supersymmetric moduli: decays to WIMPs

In light of above, if there is a stable WIMP, will be produced copiously in decays of supersymmetric moduli. To avoid overproduction, require that temperature after decay high enough that WIMPs in thermal equilibrium. Implies a very large mass for the moduli, 10^6 GeV or larger.

Non-supersymmetric Moduli

It has been argued that WIMP dark matter might be the result of non-supersymmetric moduli decays, particularly in models of split susy. But in light of the equality of decays to particles and superpartners, except in special kinematic regions, one expects an order one fraction of the energy density, immediately after moduli decays, to be in WIMPs, and this is problematic.

Avoid, e.g., if moduli are lighter than WIMPs. Note this is not compatible with split spectrum. Alternatively avoid if no WIMPs (broken R parity).

Axions as Dark Matter

Instead, axions as dark matter. Now if require that correct density (anthropic, e.g. as in Nomura, Shirai?) one sets an *upper* limit on moduli masses of order 10's of TeV. Lower limit from nucleosynthesis (view as a fact, or perhaps try to understand anthropically; e.g. structure formation?).

So another pointer to scale a 10's of TeV.

Arguments for/against higher scales of Supersymmetry Breaking

From value of the Higgs mass: For a broad range of tan β, susy at 10's-100's of TeV. For a narrow range, higher. 10^4 advocated by Arkani-Hamed et al; resolves problems of flavor changing neutral currents, even with anarchic supersymmetry breaking. Coupled with split susy (anomaly mediation) a picture including dark matter.

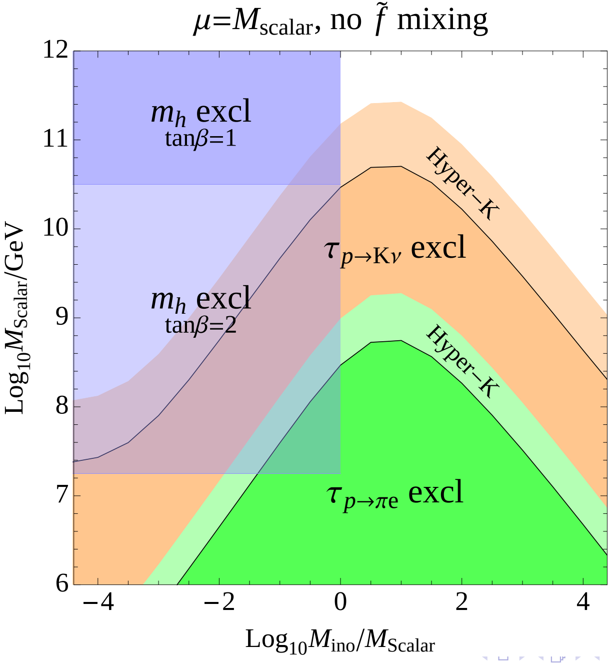
But argument seems weak. Split susy not obviously generic. Narrow tan β range. Moduli issues as above – problem of obtaining high temperatures. In addition: 10^4 TeV: proton decay

If soft breakings anarchic, a problem with proton decay through *dimension five* operators.

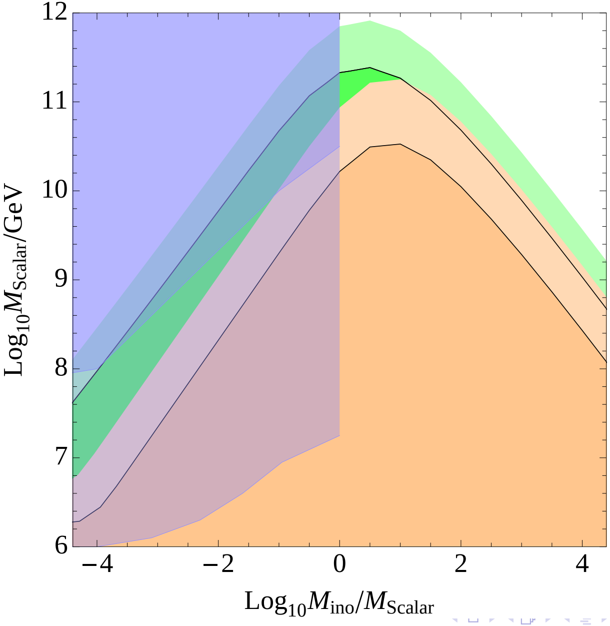
Proton Decay Through Dimension Five Operators

SU(5) models: usually assumed that dimension five operators arise through exchange of color triplet Higgs, and that corresponding Yukawa's related by SU(5) symmetry (simple Higgs structure). Results in suppression of dimension five operators by products of light quark, lepton masses; still not consistent with existing limits.

But if no underlying flavor structure, might expect, in general, dimension five operators $QQQL$, $\bar{u}\bar{u}\bar{d}\bar{e}$ with "anarchic" coefficients. In order that adequately suppressed, need very high scale of supersymmetry breaking, 10^{10} TeV or so. [P. Draper, W. Shepherd, M.D.]


$\mu = M_{\rm scalar}$, no $\tilde{f}$ mixing
m_h excl
$\tan\beta=1$
m_h excl
$\tan\beta=2$
Hyper–K
$\tau_{p\to K\nu}$ excl
Hyper–K
$\tau_{p\to\pi e}$ excl
12
11
10
9
8
7
6
−4
−2
0
2
4
$\mathrm{Log}_{10}M_{\rm Scalar}/\mathrm{GeV}$
$\mathrm{Log}_{10}M_{\rm ino}/M_{\rm Scalar}$

$\mu = M_{\rm ino}$, large $\tilde{f}$ mixing



Even simple models of horizontal symmetry (“alignment"), with susy breaking scale at 10 TeV, more than adequately suppress flavor changing neutral currents, B, L violation. So argument for very high scale of susy breaking is not compelling. [Leurer, Nir, Seiberg;Ben-Hamo, Nir,; Draper, Shepherd, M.D.]

Genericity of Split Spectrum

Usual argument: Gauginos are fermions, fermion masses can be protected by chiral symmetries.

But *argument suspect*: any such symmetry is an R symmetry. Necessarily broken to account for small cosmological constant. (This breaking is reflected in the usual anomaly-mediated mass formula).

Need to look more microscopically at mechanism of supersymmetry breaking, *R* breaking.

Retrofitting: A generic form of (metastable) dynamical supersymmetry breaking

Field X with coupling XW_α^2. X a pseudomodulus. If couples to other fields, naturally stabilized at point where these are light.

In such models, $F_X \neq 0$, naturally couples to SM fields as well (no suppression of gaugino masses).

So not clear that “split" is generic [M.Bose, M.D.], but might be true.

Can generate μ term, other dimensionful couplings through retrofitting as well.

What apparent failures of naturalness may be telling us

1. Things are natural – just be patient (and/or more clever!).
2. There just is a large hierarchy
3. Supersymmetry is there – just a bit unnatural. We motivated a picture for the scale based on landscape ideas, axion as dark matter and associated constraints.