Alternative Futures for Particle Physics

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Workshop: Why is the Higgs Mass 126 GeV, Madrid, 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 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.

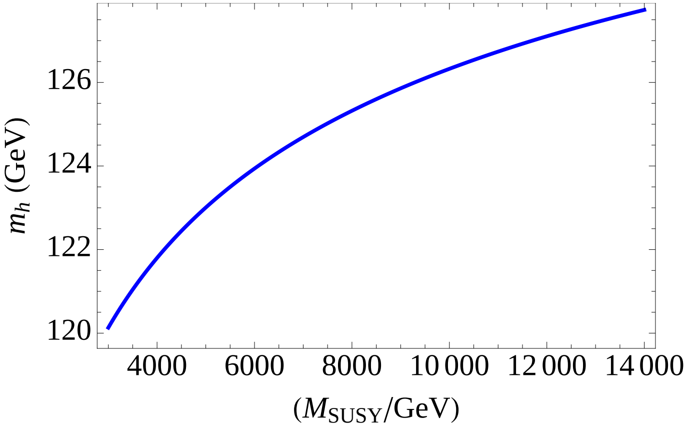
Higgs Discovery; LHC Exclusions

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:



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

Physics in Crisis?

http://blog.physicsworld.com/2013/09/12/
perimeter-institute-welcome-speech-reignites-the-st
http://www.math.columbia.edu/~woit/wordpress/
?p=6238p

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 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 gluino mass (of order 1.4 TeV) feeds into stop. Typically leads to few percent fine tuning (Arvinataki, Villadoro, et al thorough review recently; others)

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, 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.

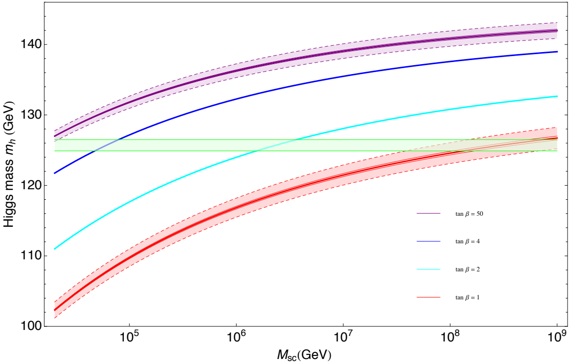
Particle physics will have a clearcut program of elucidating these new phenomenon for many years.

The happiest outcome.

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

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 $\tan\beta$ (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.

Extremely tuned (non-existent?) supersymmetry

Perhaps anthropic considerations account for huge tuning of Higgs mass. Underlying scale large.

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
3. Coupling constant unification
4. Natural dark matter candidates

A Non-Standard argument for some degree of supersymmetry

Apart from the standard arguments, there is another argument for some degree of supersymmetry: vacuum stability.

In a landscape context, if no susy, our vacuum is a state of accidentally small c.c., surrounding by a vast number of states of negative c.c. Why stable?

Need to suppress decays to *every* state. Small coupling (string coupling), large volume: don't help significantly. Problem emphasized recently by Greene, Weinberg.

Simplest way to account for stability?

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:

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

Landscape as a Model for Questions of Naturalness

Landscape models have many limitations (more from Douglas at this meeting). 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!"

Branches of the Landscape

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

1. No supersymmetry
2. Supersymmetry, no (discrete) *R* symmetries
3. Supersymmetry, discrete *R* symmetries.

On (2), cosmological constant requirement (ignoring Higgs) suggests uniform distribution of susy scales on a log scale. For (3), concentration at low scales. We will hear more about these from Michael Douglas at this meeting.

How populated? Counting/cosmology? Argument above suggests that, for (1), non-susy states might not be so common (how to quantify?). Simple considerations for flux vacua suggest that states with symmetries are rare.

Aside: Landscape and Symmetries

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

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.

Phenomenological Pointers for the Scale of Supersymmetry Breaking

In any case, a strong argument for some degree of low energy supersymmetry, possibly at low scales. How low?

For a broad range of tan β, susy at 10's-100's of TeV.

A phenomenological argument against 10^4 TeV: proton decay

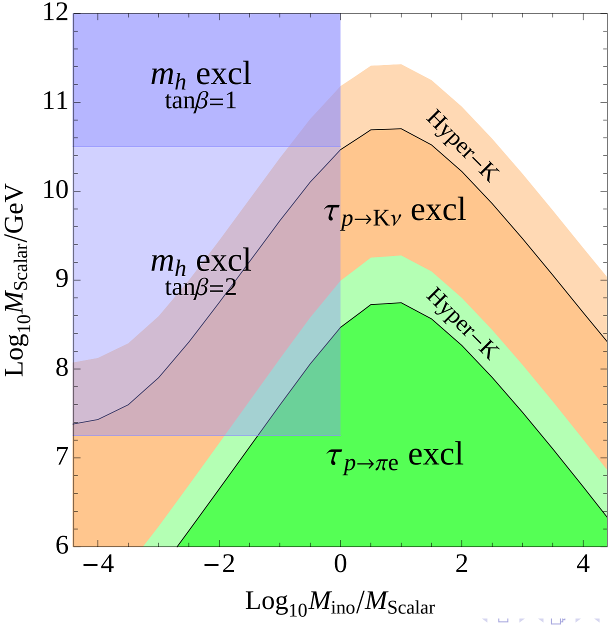
If soft breakings anarchic, a problem with proton decay through *dimension five* operators.

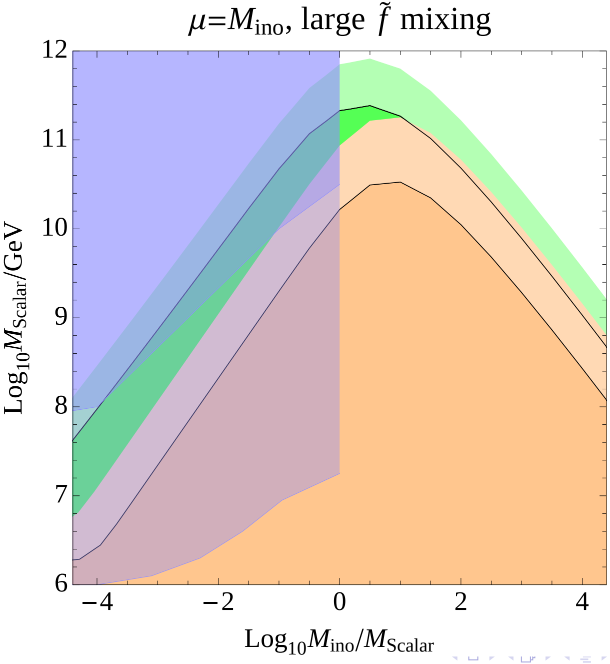
Proton Decay Through Dimension Five Operators

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





$\mu = M_{\rm ino}$, large $\tilde{f}$ mixing
$\mathrm{Log}_{10} M_{\rm Scalar}/\mathrm{GeV}$
$\mathrm{Log}_{10} M_{\rm ino}/M_{\rm Scalar}$

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.

A pointer to Scales: The Cosmological Moduli Problem

Ibanez et al, Banks, Kaplan and Nelson: moduli in string theory lead to cosmological difficulties.

Require: reheating to temperatures of order 10 MeV or higher. Requires moduli masses (assuming decay through Planck suppressed operators) 30 TeV or higher.

If operative, suggests a high scale of supersymmetry breaking. Dark matter not produced thermally. Late generation of baryon asymmetry.

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:

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

E.g. from

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

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: $\phi \to A_\mu + A_\mu$ and $\phi \to \lambda\lambda$. 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 produced in moduli decays. 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 probably not compatible with split spectrum. Alternatively avoid if no WIMPs (broken R parity).

Ways one might understand a modest hierarchy

1. In inflationary models, if inflaton and susy breaking dynamics connected, may have countervailing pressures: low inflation scale tuned, light higgs with high susy breaking scale tuned.
2. Dark matter, moduli problems may provide pressure to higher scales.
3. Limitations of discrete tuning (M. Bose, Dine)

None of these is convincing at this stage, nor do they point reliably to a particular scale for supersymmetry breaking.

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 energy scales.
   - Split supersymmetry: LHC discovery of light gluino
   - Unsplit – Intensity frontier provides evidence for a new scale at 10's of TeV ($\mu \to e + \gamma$; d_n). *Eventually* able to probe this scale.
3. Big failure of naturalness

Outline:

1. Justify focus on supersymmetry. Unification, dark matter(?), mdsb,
2. Possible alternatives: still natural. Extra dof; r parity violation. But very squeezed. Some elaboration on these ideas, e.g. gauge mediation with flavor (Shih, Shadmi; mfv and r parity, but limitations.) Mention some of our work on mfv.
3. Somewhat tuned – A parameter dependence. discuss mini split and various versions. Could mention motivation from anomaly mediation. Genericity.
4. Very tuned – here discuss flavor, proton decay.
5. Extremely tuned.
6. Moduli problem as a guide to thinking about these issues.
7. Discrete Tuning