Recent theory developments: implications for low energy supersymmetry

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SUSY at the LHC?

The good news: The theoretical arguments for low energy supersymmetry seem sharper than ever.

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Whether or not supersymmetry is a symmetry of low energy physics, supersymmetric theories continue to provide an exceptional laboratory for the study of field theory and string theory.

Outline

- Some recent theoretical developments: constraints on susy breaking, non-linear lagrangians, susy currents; cft's, constraints on low energy susy lagrangians, exact beta functions [very brief].
- SUSY models for low energy physics: metastable dynamical supersymmetry breaking
- SUSY models for low energy physics: mediation mechanisms
- Low energy supersymmetry: for and against.

Progress in Supersymmetric Field Theories (and related String Developments)

Selected topics, for brief treatment:

1. Theoretical Aspects of Supersymmetry Breaking, Gauge Mediation
2. Conformal field theories
3. String theories and symmetries
4. Effective lagrangians for supersymmetry breaking
5. Current multiplet structures
6. Understanding the Exact Beta Function and Related Issues

Theoretical Aspects of Gauge Mediation

The last few years have seen a number of developments in our understanding of supersymmetric theories with broken supersymmetries, both non-dynamical (O'Raifeartaigh) and dynamical.

1. O'Raifeartaigh models: theorems about R- breaking: no breaking in models with *R* charges 0 and 2 only [Shadmi, Mason: hidden assumptions allow exceptions]; examples of spontaneous *R* breaking (Shih).
2. General Gauge Mediation: more precisely, a general theory of gauge mediation (Meade, Seiberg, Shih)
3. General Messenger Gauge Mediation: one can analyze, in great generality, theories of gauge mediation with three sectors, the MSSM (or enlarged), a supersymmetry breaking sector, and a mediator sector. Certain features of the spectra of these theories can be shown to be quite general (Dumitrescu, Komargodski, Seiberg, Shih). .

String theories and symmetries

Banks, Seiberg: from considerations of discrete symmetries in supergravity, refined arguments for absence of continuous global symmetries, non-compact gauge symmetries.

Guidance for model building.

Conformal Field Theories

Proof of the “a -theorem", that there is a quantity, as conjectured by Cardy, that always decreases along renormalization group flow.

Proof (Kormargodski, Schwimmer) relies on study of scattering amplitudes for a background dilaton, use of unitarity.

Supercurrent Multiplets, Effective lagrangians for supersymmetry breaking

(Seiberg, Komargodski) Improved understanding of supercurrent multiplet structure. Simple superfield description of non-linear field theories. X_{NL}: fermion is Goldstino. Constraint $X_{NL}^2 = 0$. Variations for theories with additional light fields, such as axions.

Applications:

1. Consistency constraints on Fayet-Iliopoulos terms, D-term supersymmetry breaking
2. Consistency conditions on non-linear sigma models (implications for string moduli fixing)
3. Effective actions for gravitinos, R axions.
4. Inflationary models sometimes described by such effective theories.
5. General Bound on the superpotential (Festuccia, Komargodski, M.D.): $\langle W \rangle < \frac{1}{2} f_r F$.

Understanding of the Exact Beta Function

It has been more than 25 years since Novikov, Shifman, Vainshtein and Zakharov noted that the *holomorphic* gauge coupling should be saturated at one loop, and proposed an *exact* β function for the *physical* coupling. In the case of an $SU(N)$ gauge theory without matter:

$$\beta(g) = -\frac{3N\frac{g^3}{16\pi^2}}{1 - 2N\frac{g^2}{16\pi^2}}. \quad (1)$$

The question has long been: in what scheme does this formula hold. This question has been widely studied in the past and further clarified recently (Festuccia, Pack, Park, Ubaldi, Wu, M.D.).

Related: why does an instanton computation in this theory, which seems to receive no perturbative corrections, yield the *wrong* answer.

Exploit, for example, finiteness of $N = 4$ theory. (Arkani-Hamed, Murayama). In $N = 1$ language, theory is often presented as:

$$\mathcal{L} = \int d^4\theta \frac{1}{g^2} \Phi_i^\dagger \Phi_i - \frac{1}{32\pi^2} \int d^2\theta \left(\frac{8\pi^2}{g^2} + i\theta \right) W_\alpha^2 \qquad (2)$$

$$+ \int d^2\theta \frac{1}{g^2} \Phi_1 \Phi_2 \Phi_3 + \text{c.c.} \qquad (3)$$

Adding mass terms for Φ_i one has a regulated version of pure susy Yang-Mills.

But, in this form, the action is not manifestly holomorphic in τ. Before adding masses,

$$\Phi_i \to g^{2/3} \Phi_i. \qquad (4)$$

Now add mass terms for the Φ_i's:

$$\mathcal{L} = \int d^4\theta \frac{1}{g^{2/3}} \Phi_i^\dagger \Phi_i - \frac{1}{32\pi^2} \int d^2\theta \left(\frac{8\pi^2}{g^2} + i\theta \right) W_\alpha^2 \tag{5}$$

$$+ \int d^2\theta (\Phi_1 \Phi_2 \Phi_3 + m_{hol} \Phi_i \Phi_i + \mathrm{c.c.}). \tag{6}$$

In this form, the low energy effective action *must* be holomorphic in τ, and it is:

$$\frac{8\pi^2}{g^2(m_1)} = \frac{8\pi^2}{g^2(m_2)} + 3N \log(m_{hol}^{(1)}/m_{hol}^{(2)}). \tag{7}$$

At tree level, the physical regulator mass is $\mu = m_{phys} = g^{2/3} m_{hol}$.

$$\beta(g) = \mu \frac{\partial g}{\partial \mu} \tag{8}$$

is the NSVZ beta function.

A Class of Renormalization Schemes

But beyond leading order, $g^{2/3} m_{hol}$ is not the location of the pole in the regulator propagator. One can equally well take

$$\mu = g^{2/3}(1 + a\frac{g^2}{16\pi^2} + \ldots) m_{hol}$$

defining a *class* of renormalization schemes.

One might choose a (and higher order coefficients) to coincide with the pole, but a is non-zero!

The Instanton Computation

Resolution of the discrepancy: while in a formal perturbation theory about the instanton, there are no corrections to the Green's function ($SU(2)$):

$$G(x) = \langle \lambda(x)\lambda(x)\lambda(0)\lambda(0) \tag{9}$$

dilute gas corrections, if present, are necessarily ir divergent (just dimensional analysis); if cut off at Λ, of the same order as the leading result. I.e. no argument that there are not order one corrections from the topological charge 1 sector.

The work of Dorey, Hollowood, Khoze, Mattis and Lee shows unambiguously that the single instanton does not saturate the topological charge one contribution.

SUSY at Low Energies: Reasons to Doubt

1. Longstanding: Cosmological constant. Doesn't seem to be solved in a "natural" way. Only coherent proposal: *landscape*. Laws of physics we observe selected from an ensemble of possible theories in some way. If this is the case, why not also m_H^2? Perhaps simply anthropic?
2. Longstanding: Non-observation of SUSY at LEP, Tevatron; LEP Higgs limit. Already hard to reconcile with conventional ideas about naturalness.
3. Early LHC: Increasing discomfort.

Theoretical arguments in favor:

1. Longstanding: technical naturalness, precision electroweak, unification, dark matter.
2. More recent: vast array of new models for *dynamical supersymmetry breaking*, exploiting *metastability* (ISS). Dynamical Supersymmetry Breaking Generic.
3. Arguments even within landscape, which might favor low energy supersymmetry. In fact, *landscape provides a potentially more sophisticated understanding of naturalness.*

Plan for Remainder

Can't cover all of these topics in detail in 15 minutes, so will just touch on a few developments:

1. A simple, flexible framework for metastable supersymmetry breaking: retrofitting.
2. Vacuum stability and supersymmetry
3. Revisiting Naturalness

It is often said that SUSY breaking is a poorly understood problem. But much has been known for many years; problem is that models were complicated. Stable, dynamical SUSY breaking requires special features which are not particularly generic. Model building is hard.

All of this changed with work of Intriligator, Shih and Seiberg (ISS): Focus on *metastable* susy breaking.

The ISS models are theoretically rich and instructive, but not necessarily appealing as a microscopic model of nature. Additional, non-dynamical, scales; unbroken, approximate R symmetry in simplest versions (Shadmi: new direction recently).

Simple OR model:

$$W = X(\lambda A^2 - f) + mAY \tag{10}$$

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

$$X \to e^{2i\alpha} X \quad Y \to e^{2i\alpha} Y \quad A \to A \qquad \theta \to e^{i\alpha}\theta. \tag{11}$$

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

$$W = X(\lambda A^2 - f) + mAY + \frac{X^{N+1}}{M_p^{N-2}} + \ldots \qquad (12)$$

(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.

Generalized Gaugino Condensation

Gaugino condensation a crucial element in understanding of SUSY dynamics.

Essence: breaks a discrete R symmetry, mass gap (dimensional transmutation).

Generalize: (J. Kehayias, M.D.; precursors: Yanagida, Izawa)

E.g. $SU(N)$, N_f quarks, $Q_f, \bar{Q}_{\bar{f}}$, coupled to singlets, S:

$$W \sim S\bar{Q}Q + S^3. \tag{13}$$

Non-zero $< \lambda\lambda >, < \bar{Q}Q >, < S >$. Break a discrete Z_{3N-N_f} symmetry.

Retrofitting O'Raifeartaigh Models

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

$$W = W = X(\lambda A^2 - f) + mAY \Rightarrow X(\lambda A^2 - \frac{S^3}{M_p}) + \kappa SAY \quad (14)$$

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):

$$\langle W \rangle \sim f M_p \quad (15)$$

Model building issues:

1. (Approximate) R symmetry breaking: retrofit models of Shih, or retrofit small, explicit breaking (challenging)
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 $\tan\beta$ (implements an idea of Rattazzi, Sarid; Gabrielli, Sarid).
4. Scale of susy breaking: many possibilities.

A rich space of models to explore.

Damocles Sword: The Landscape

The small – and very peculiar – value of the cosmological constant suggests breakdown of naturalness.

Landscape (Banks, Weinberg, Bousso, Polchinski...) only compelling explanation so far offered, and has a triumph (prediction of dark energy) to its credit.

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.

We associate a probability distribution with this ensemble; microscopically, this depends on the underlying microphysics (string theory? some larger structure incorporating gravity?), cosmology, other unknown features.

Model Building in the Landscape Era

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"]

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 of SUSY (also motivated by IIB studies): favors low scale susy. (Gorbatov, Thomas, M.D.)

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 this questions.

Little Hierarchy?

More refined “models" can give little or “medium size" hierarchies. E.g. tension between scale of inflation (preferably high) and Higgs mass (low).

Other related questions: Does one expect symmetries (as in the retrofitted models, and as needed to suppress proton decay, etc.?). Naive landscape counting in flux models: no! (Z. Sun, M.D.).

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

A cosmological argument for low scale susy in the landscape:

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.):

$$\Gamma \propto e^{-2\pi^2 \left(\frac{M_p^2}{m_{3/2}^2} \right)} \tag{16}$$

What's next?

We have an exquisite understanding of supersymmetric theories, and plausible ideas of how they could address some of the most pressing questions in particle physics. Further improvements are certain.

But our naive ideas about naturalness are under stress, both from experiment and from theory. A possible Higgs discovery – and knowledge of the Higgs mass – and further experimental constriction the supersymmetry parameter space (or a discovery!) – will focus our thinking sharply.