Ramifications of Discrete R Symmetries

Rethinking Naturalness

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Supersymmetry Under Stress

Even prior to the LHC launch, supersymmetry seemed to be working hard to hide itself. Flavor violation (esp. in the B system), CP violation, a Higgs well above the Z mass, and super partners not far from M_Z, all seemed likely outcomes of “generic" models of supersymmetry. The LHC has already pushed the supersymmetry envelope much further.

1. Exclusions of super particles are at the TeV level, except in special regions of the supersymmetry parameter space.
2. A Higgs mass of 125 is very uncomfortable for most ideas about supersymmetry. Few would have predicted a mass this high.

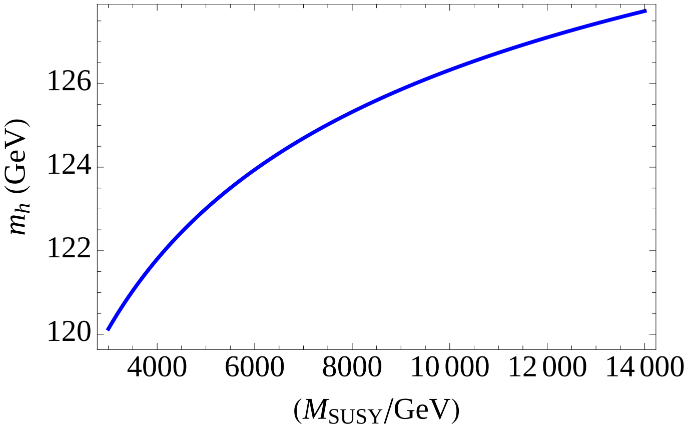
Implications of the Higgs Discovery for Supersymmetry

Higgs at 125 GeV poses two challenges:

1. In MSSM, $m_h \leq M_Z$. Radiative corrections can be large, esp. for large tan beta, large $\tilde{m}_t$, and/or large A. Alternatively, additional degrees of freedom (NMSSM).
2. Large $\tilde{m}_t$ implies significant fine tuning of Higgs mass:

$$\delta m_h^2 = -6 \tilde{m}_t^2 \frac{y_t^2}{16\pi^2} \log(\Lambda/\tilde{m}_t) \tag{1}$$

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



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

But perhaps one shouldn't be so negative. First, there are some regions of the parameter space left which are not so tuned. These are referred to these days as “natural supersymmetry":

1. light stops to reduce the fine tuning of the Higgs mass, with large A terms or additional singlets to account for the observed Higgs mass.
2. Other proposals, e.g. in gauge mediation involving mixing of messengers and Higgs, focus point supersymmetry; RPV with MFV (Grossman, this meeting; pursuing microscopic version with A. Monteux).

Second, supersymmetry remains an extremely attractive theory for Beyond the Standard Model Physics.

1. It can account for [large] hierarchies. (a) It does not suffer from the problem of quadratic divergences.
2. It can account for [large] hierarchies. (b) Dynamical breaking of supersymmetry can give rise to exponentially large hierarchies between the Planck or unification scale and the weak scale.
3. Other proposals to account for hierarchies (technicolor, warping...) are hard to reconcile with precision electroweak physics, flavor constraints, and now the apparent existence of what appears to be an elementary Higgs field.
4. Unification
5. Dark matter

Unnatural Supersymmetry

There is another viewpoint on these questions. We know one other quantity in nature which appears extremely tuned: the cosmological constant (dark energy). We have no good ideas based on symmetries or dynamics for its value, which is incredibly small from any particle physics expectations. In particular, no plausible [my opinion, but widely shared] explanation which leads to new light degrees of freedom has been proposed. At the very least, we have to accept that there may be resolutions which we have not thought of, possibly without low energy consequences. [Landscape, for better or worse, most plausible existing model]

There are many claims that in a landscape framework, tunings of various sorts are two be expected. E.g. (Susskind, Douglas based on work of Douglas, Denef; Sun, M.D.) – no low energy supersymmetry (motivated first “split susy models, with very large splittings).

We might despair, then. But perhaps there is some more intermediate story. To start, a Higgs mass of 125 GeV gives some reason for optimism. If the typical susy particles had masses of order 10's to 1000's of TeV, they can account for this mass. Such masses would ameliorate or eliminate problems of flavor in supersymmetry, and solve the cosmological moduli problem. This viewpoint has been most strongly advocated recently by Arkani-Hamed et al, Dimopoulos et al, based on their earlier work on "split supersymmetry."; Kane et al (this meeting); Heckman (this meeting); Linde, Dudas (this meeting). Discussion of Nomura yesterday.

More detailed landscape studies suggest low energy supersymmetry *might* be favored, if there are many states in the landscape with dynamical supersymmetry breaking. (Gorbatov, Thomas, M.D.) Perhaps some anthropic/landscape configuration accounts for a modest tuning (more later).

Plan of the Talk

1. The genericity of metastable dynamical supersymmetry breaking (DSB)
2. The special role of (discrete) R Symmetries – Nelson-Seiberg, cosmological constant,...
3. Dynamical Breaking of R symmetry.
4. R Symmetries and anomalies. Implications (R parity violation; model building generally)
5. Retrofitting Gauge Mediation – successful models
6. Retrofitting Gravity Mediation – genericity of split susy
7. Origins of Tuning

For the last few decades, as we waited for the LHC (and SSC!), we have been able to be lazy. Relied on naturalness, dark matter, unification; didn't worry too much whether we had compelling susy models. If we are contemplating tuning, absent data, we would like to have something compelling, **generic.**

Elaborate models to explain real data are one thing; Rube Goldberg contraptions to explain absence of data are more problematic.

Today: “New, Improved" Models of Dynamical Supersymmetry Breaking

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 chiral representations of gauge groups, other 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.

Metastable Supersymmetry Breaking

Quite generic. First, non-dynamical.
O'Raifeartaigh Model:

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

SUSY broken, can't simultaneously satisfy

$$\frac{\partial W}{\partial X} = \frac{\partial W}{\partial Y} = 0. \tag{3}$$

E.g. $m^2 > f$ gives $\langle A \rangle = \langle Y \rangle = 0$, $\langle X \rangle$ undetermined by the classical equations. f is order parameter of susy breaking.

This model has a continuous "R Symmetry". In accord with a theorem of Nelson and Seiberg, which asserts that such a symmetry is required, generically, for supersymmetry breaking.. In components, using the same labels for the scalar component of a chiral field and the field itself:

$$X \to e^{2i\alpha} X \quad Y \to e^{2i\alpha Y} \quad A \to A \tag{4}$$

while the fermions in the multiplet have R charge smaller by one unit, e.g.

$$\psi_X \to e^{i\alpha}\psi_X \quad \psi_Y \to e^{i\alpha}\psi_Y \quad \psi_A \to e^{-i\alpha}\psi_A. \tag{5}$$

(In superspace, this corresponds to $\theta \to e^{i\alpha\theta}$ $d\theta \to e^{-i\alpha} d\theta$.)

Under an R symmetry, the supercharges and the superpotential transform:

$$Q_\alpha \to e^{i\alpha} Q_\alpha \quad \bar{Q}_{\dot{\alpha}} \to e^{-i\alpha} \bar{Q}_{\dot{\alpha}} \quad W \to e^{2i\alpha} W. \tag{6}$$

One loop effects generate a potential for X (Coleman-Weinberg) with minimum at $\langle X \rangle = 0$.

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. $\alpha = 2\pi/N$; a *discrete* R symmetry (Z_N) Allows

$$W = X(\lambda A^2 - f) + mAY + \frac{X^{N+1}}{M^{N-2}} + \dots \tag{7}$$

$$W \to \omega^2 W; \quad \omega = e^{\frac{2\pi i}{N}}. \tag{8}$$

(We will assume $M \sim M_p$).
At low energies the last term is irrelevant, so in this model, there is a continuous R symmetry as an accidental consequence of the discrete symmetries (the model can be the most general consistent with symmetries).

One expects that the model has supersymmetric vacua, and it does:

$$X = (fM^{N-2})^{1/N+1}. \tag{9}$$

But the minimum near the origin persists (now a local minimum), with positive energy ($\approx f^2$), so the susy-breaking vacuum is *metastable*.

A Generic consequence of the Nelson-Seiberg theorem and the absence of continuous symmetries.

R Symmetries and the Cosmological Constant

Before proceeding further, another important feature of R symmetries should be noted. They can account for the small $|\langle W \rangle|$ necessary to understand the cosmological constant. This last point will be important to us. In supergravity:

$$V = e^K \left[|\frac{\partial W}{\partial \phi_i}|^2 - 3|W|^2 \right] \tag{10}$$

This is somewhat schematic, but the point is that to obtain a small or negative cosmological constant requires a non-zero $\langle W \rangle$. W necessarily transforms under the R symmetry so:

- Small cosmological constant requires non-zero W and thus breaking of the R symmetry
- The smallness of W can be related to the smallness of R symmetry breaking; would like scale of R breaking to be related to scale of susy breaking.

Retrofitting: Supersymmetry Breaking Made (too?) Easy

ISS: A beautiful dynamical example. In simplest versions number of limitations:

1. Additional mass scales put in by hand
2. Approximate *R* symmetries require gymnastics to obtain massive gauginos, μ-term.
3. Additional dynamics or a bizarre constant required to understand the smallness of the cosmological constant (value of *W*).

Various solutions proposed.

I will focus on models which are, at first sight, somewhat more ad hoc, but on second look simpler and more generic. "Retrofitting". Conceptually (morally) in a class with the ISS models.

Would like to generate the scale, f, of the O'Raifeartaigh model dynamically.

Basic ingredient: dynamical generation of a scale, without susy breaking.

Candidate mechanism: gaugino condensation.

Dynamical Breaking of Discrete R Symmetries

Pure supersymmetric gauge theory: A^a_μ, λ^a.

Possesses a discrete Z_N R symmetry under which

$$\lambda \to e^{\frac{2\pi i}{N}} \lambda. \tag{11}$$

This symmetry is spontaneously broken by the gaugino condensate:

$$\langle \lambda\lambda \rangle = \Lambda^3. \tag{12}$$

Well understood dynamics. Supersymmetry unbroken. Non-zero superpotential at lower energies:

$$\langle W \rangle = -\frac{1}{4g^2} \langle W_\alpha^2 \rangle = \Lambda^3. \tag{13}$$

These phenomena – dynamical breaking of a discrete symmetry with dimensional transmutation and unbroken supersymmetry, occur in a wider range of theories. These are of interest as there are order parameters of lower dimension than W_α^2.

E.g. consider an $SU(N)$ gauge theory with N_f flavors, $Q_f, \bar{Q}_f$. Include, in addition, a singlet, and a tree level superpotential

$$W = y_f S \bar{Q}_f Q_f + \lambda S^3. \tag{14}$$

This model possesses a Z_{3N-N_f} discrete symmetry (seen from instantons). For small λ, $\lambda \ll y_f$, one expects that S obtains a large expectation value, and one can integrate out the Q_f, $\bar{Q}_f$ fields. This yields a superpotential

$$W_{eff} = \left(\prod_{f=1}^{N_f} y_f S \right)^{1/N} + \lambda S^3 \qquad (15)$$

The equation $\frac{\partial W}{\partial S} = 0$ has $3N - N_f$ roots, breaking the discrete symmetry. (Note that there are also continuous flat directions, disconnected from these).

There are many variants on this model, e.g. with more scalars, or with more scales:

$$S_1 \bar{Q}_1 Q_1 + \frac{S_2^2}{M_p} \bar{Q}_2 Q_2 + S_1^3 + \frac{S_2^4}{M_p} \tag{16}$$

with more intricate discrete symmetries and scalings.

Retrofitting the O'Raifeartaigh Models

We can take the earlier OR and render it a model of MDSB by model by making the replacements:

$$W = W = X(\lambda A^2 - f) + mAY \Rightarrow X(\lambda A^2 - \frac{aW_\alpha^2}{M_p}) + \kappa SAY \quad (17)$$

(other scalings possible).

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):

$$\langle W \rangle \sim f\, M_p \quad (18)$$

Clearly tip of a large iceberg. Many variants: fields, couplings, scales (powers of S, W_α^2, determining dimensional parameters).

Anomalies and *R* Symmetries

Before attempting to build models of gravity, gauge mediation, a harder look at *R* symmetries:

Going back to work of Ibanez and Ross (earlier Krauss and Wilczek) much discussion of anomaly constraints in low energy theory for discrete symmetries. Banks and M.D. pointed out that such constraints can only reliably be applied to anomalies with non-abelian symmetries, where instantons provide a low energy test. Also pointed out the possibility of Green-Schwarz cancellations. There is extensive literature about possible anomaly-free discrete *R* symmetries in the MSSM, and using these to constraint possible low energy physics. Much of this literature includes the possibility of GS cancellations.

But there are at least two reasons to question the imposition of these generalized Ibanez-Ross constraints.

1. The R symmetry is necessarily a broken symmetry, broken at some high energy scale. We have seen simple models in which scalar field vev's break the R symmetry; these could give rise to large masses for fields which contribute to the anomaly.
2. Most studies in string theory of discrete anomalies have been conducted in the heterotic string, and in these theories, any would-be anomalies can be cancelled by assigning the dilaton supermultiplet a non-linear transformation law. It is not clear how general these models are, and whether there couldn't be instances in which several moduli (i.e. some linear combination of moduli) transform nonlinearly.

Indeed, in the heterotic examples studied to date, one can give an argument why no such cancellations. In all of these cases, there are points in the moduli space where all of the moduli, except for the dilaton, transform under enhanced symmetries. Thus there can be no RW_α^2 coupling. As one moves from this point, only vector like sets of fields (under the discrete symmetry and other unbroken symmetries) gain mass, so no additional GS term. This applies to orbifolds and to Calabi-Yau spaces with Gepner points.

Perhaps in some broader class of theories, without such enhanced symmetry points, one might find more complicated anomaly cancellations (in progress with Angelo Monteux).

Building models of low energy gauge mediation:

1. (Approximate) R symmetry breaking: retrofit models of Shih, in which breaking is spontaneous, or retrofit explicit breaking terms. E.g., in messenger sector,

$$W_{mess} = X \frac{S}{M_p} \bar{M} M + \frac{\gamma\, S^2}{M_p} \bar{M} M. \qquad (19)$$

2. μ term: Retrofit as well: $\lambda S H_U H_D$. $< F_S > \ll S^2 \Rightarrow$ Small B_μ, large $\tan\beta$
3. Scale of susy breaking: many possibilities.

Requiring small cc (without introducing further dynamics) and insisting on a discrete *R* symmetry greatly limits the possibilities for the underlying scale of supersymmetry breaking. Enumerating models consistent with a reasonable set of conditions is a problem currently under study. (with M. Bose)

Allowing some degree of tuning is probably necessary for any realistic theory of gauge mediation. E.g. (absent large A terms; see talk by D. Shih at this meeting) one might want top squarks at about 8 TeV. Then one would expect lepton doublets at about 2 TeV, and gluiness and charginos similarly. This corresponds to a tuning of a part in 500 or so for the Higgs mass.

Various problems of usual gauge mediation are ameliorated in this framework, esp. CP, $b \to s + \gamma$. Flavor is now more interesting in that one could contemplate a rather high scale of supersymmetry breaking, corresponding to graviton masses of order 100's of GeV.

Gravity Mediation Retrofitted

We can also retrofit gravity mediation.

In this discussion, we will assume a “modest" hierarchy ($m_{3/2} \sim 5 - 1000$ TeV). Our main interest is whether there are any predictions from such a structure, and in particular whether some form of “split supersymmetry" generically emerges.

Split susy: gaugino masses lighter by a loop factor than scalar masses. Usually motivated by statement that while scalars cannot be protected by symmetries, fermions (gauginos) can.

But any symmetry under which gauginos transform is necessarily an R symmetry, and any such symmetry, we have seen, must be broken.

We'll assume a discrete R symmetry. We can again consider a coupling of the form

$$a \frac{X}{M_p} W_\alpha^2 \tag{20}$$

X has R charge zero. This is a retrofitted version of the Polonyi model. The effective superpotential is

$$W = a \frac{\Lambda^3}{M_p} X + \Lambda^3. \tag{21}$$

As for the gauge-mediated case, (near-) cancellation of the cosmological constant requires only that a is an $\mathcal{O}(1)$ number (albeit adjusted to many decimal places). This feature will not hold for other possible scales of supersymmetry breaking.

Moduli Fixing: Kahler Stabilization

Without loss of generality, we can define $X = 0$ as the location of the minimum of the X potential. we can write a Taylor series expansion of K:

$$K = k_0 + k_1 X + \text{c.c.} + k_2 X^\dagger X + \tilde{k}_2 X^2 + \text{c.c.} + \quad (22)$$

$$k_3 X X^{\dagger\,2} + \tilde{k}_3 X^3 + \text{c.c.}$$

We impose the conditions

$$V'(0) = V(0) = 0. \quad (23)$$

These are two algebraic conditions on the k_i's; they have a multiparameter set of solutions. There is no small parameter in these equations, and the k_i's (in Planck units) generically are comparable.

Given the assumption that X couples to W_α^2 of the R breaking dynamics, one would expect that it would typically couple to the W_α^2 of the standard model gauge groups. Gaugino masses are generated as a result of this coupling; they are not parameterically suppressed.

$$m_\lambda = \langle F_X \rangle = \frac{\partial W}{\partial X} + \frac{\partial K}{\partial X} W = \Lambda^3 (-\frac{1}{b} + k_1). \qquad (24)$$

So split supersymmetry does not appear particularly generic. Of course, it might arise because of accidental vanishing of some couplings, or through anthropic pressures.

Origins of Tuning

More recently, various authors have argued for scales of order 30 TeV to resolve cosmological moduli problem (Douglas, Kane). Underlying these proposals is a picture of some sort of anthropic selection.

But compelling anthropic arguments for such scales have not been put forth. Moreover, once one argues that there may be some degree of tuning, where does it stop?
What one would like is an argument for fine tuning that predicted the degree of tuning, e.g. explaining a Higgs at 125 GeV.

I won't provide an answer here, but suggest some directions:

1. Plausibly, electroweak scale is anthropic. To get started, take this as a given (many complications, e.g. complicate change of weak scale with changes of quark Yukawa's).
2. Inflation: in some models of inflation, there is a competition associated with a low scale of inflation (requiring small, tuned constants) and the scale of supersymmetry breaking, which are tied (L. Pack, M.D.)
3. Dark matter, structure: dark matter produced in moduli decays? Too early growth of structure unless moduli heavy (under study with P. Draper, but no definitive results yet).
4. Discrete choices of theory (e.g. gauge group, number of flavors in R breaking sectors) – corresponding large jumps in $m_{3/2}$ and degree of tuning for fixed weak scale (but not clear that gives required degree of tuning).
5. Discrete choices of theory: 10^5 times more states, say, on one branch than another?