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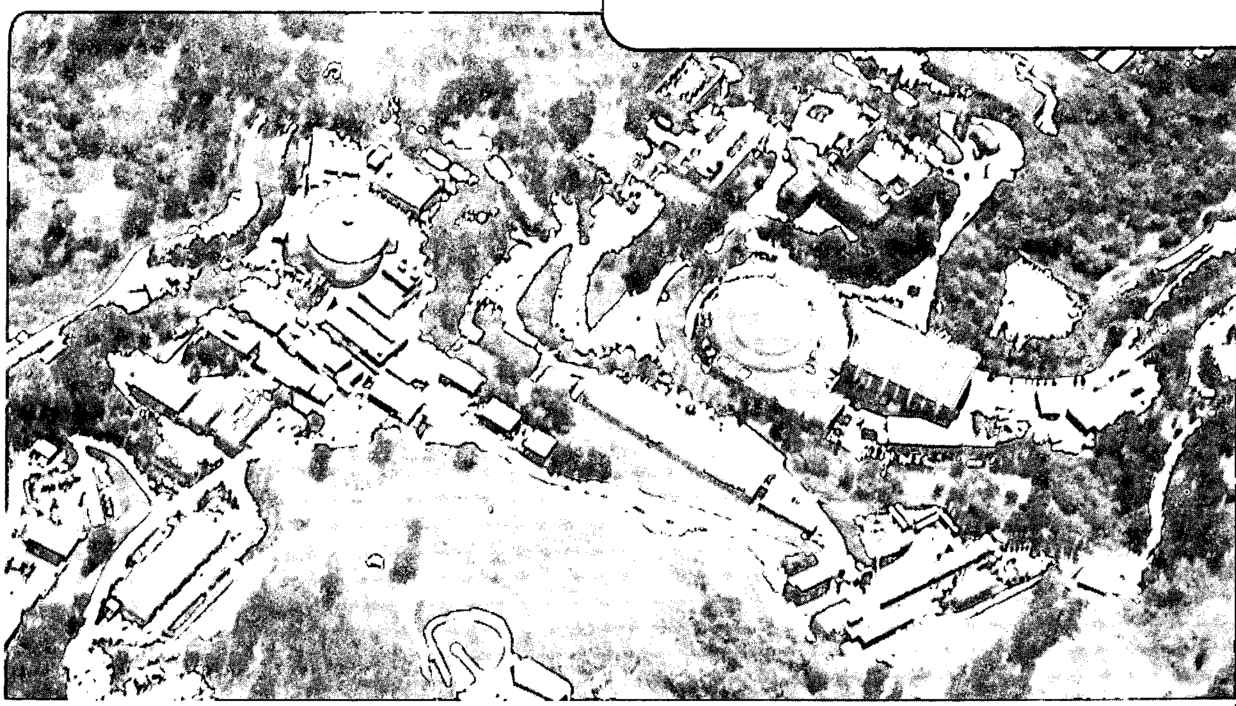

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Weak Scale Supersymmetry *†

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Abstract

An introduction to the ideas and current state of weak scale supersymmetry is given. It is shown that LEP data on Z decays has already excluded two of the most elegant models of weak scale supersymmetry.

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The LEP data on Z decays and the Fermilab Tevatron data have begun an era of strigent experimental scrutiny of the idea of supersymmetry at the weak scale. In this lecture I discuss the minimal low energy supersymmetric model (MLES) and show why it is not to be particular preferred over several other models having very different experimental signatures. I illustrate the power of the Z data by considering two models which are now excluded in their simplest forms. In one R parity is spontaneously broken by a sneutrino vacuum expectation value,[1] and in the other R parity is promoted to a continuous global $U(1)_R$ symmetry.[2]

One of the goals of the multi-TeV physics of the 1990s is to elucidate the nature of electroweak symmetry breaking and to understand the origin of the weak scale. I will follow the predominant viewpoint that the Planck scale sets the fundamental scale of mass and that all other scales are somehow derivative. This viewpoint is not obviously correct, especially in the case of Brans-Dicke gravity theories, but provides a convenient framework. The QCD scale Λ is of order $10^{-20} M_p$. Such a hierarchy of scales is understood by the gradual logarithmic renormalization of the QCD coupling. If QCD is defined at the Planck scale by the dimensionless parameter α_s, radiative corrections produce the phenomenon of dimensional transmutation: $\Lambda \cong M_p \exp(-1/\alpha_s)$. This is such a plausible and efficient way of generating scales that the idea of dimensional transmutation underlies all of our ideas for the origin of the weak scale. This is most obvious for the case of technicolor.[3] The technicolor idea is that there is a new strong force which gets strong near a TeV and which has techniquark condensates similar to the quark condensates of QCD which break light quark chiral symmetries. If the techniquarks are chiral under $SU(2) \times U(1)$ their condensates will trigger electroweak symmetry breaking. The weak scale is then identified with the dimensional transmutation scale Λ_{TC}, at which the technicolor coupling gets strong. It is possible that the Higgs boson is composite and that both the binding forces and the forces which give it a vacuum expectation value are due to some new strong gauge force, ultracolor.[4] In this case the weak scale is identified as the dimensional transmutation scale, Λ_{UC} at which the ultracolor coupling gets strong.

There are two viewpoints as to why physics may become supersymmetric above the weak scale. The more modest reason is that supersymmetry protects the Higgs mass against a quadratic divergence. If the Higgs is elementary there should be a symmetry reason explaining why it is so light. All the other particles of the standard model have symmetries protecting their masses: chiral symmetries for fermions and gauge symmetries for vectors. Supersymmetry allows a symmetry to protect scalar masses also. Supersymmetric theories have a bosonic state degenerate with each fermionic state. From the spectrum of the standard model it is obvious that if supersymmetry is relevant to nature it must be broken at least on scales of order M_W. Furthermore, for the Higgs mass to be protected to the weak scale, the supersymmetry breaking scale M_S cannot be much larger than the weak scale. We conclude that M_S must be identified with the weak scale.

A second, more ambitious, viewpoint is that the scale of supersymmetry breaking, and therefore the weak scale, is dynamically generated via a dimensional transmutation.[5] This could occur if the potential for some scalar field were flat at tree level, but had a logarithmically generated minimum via radiative corrections. Such a possibility needs supersymmetry since otherwise the flatness of the potential would be spoiled by quadratic divergences.

The minimal low energy supersymmetric model (MLES) is minimal in several senses. It involves the fewest chiral superfields necessary for a supersymmetric extension of the standard model $Q = (U, D), U^c, D^c, L = (\nu, E), E^c, H_1$ and H_2. Secondly it possesses the fewest interactions for such a model to be consistent with data. These interactions are the supersymmetric gauge interactions of $SU(3) \times SU(2) \times U(1)$, together with supersymmetric Yukawa interactions

$$f = Q\lambda_D D^c H_1 + Q\lambda_U U^c H_2 + L\lambda_E E^c H_1 + \mu H_1 H_2, \tag{1}$$

and a set of interactions which break supersymmetry softly

$$m_{\tilde{g}}\tilde{g}\tilde{g} + \ldots, \tag{2a}$$

$$m_{\tilde{q}}^2 \tilde{q}^* \tilde{q} + \ldots, \tag{2b}$$

$$A\tilde{q}\tilde{d}^c h_1 + \ldots, \tag{2c}$$

$$B h_1 h_2 + h.c., \tag{2d}$$

where lower-case letters are used for component fields, and generation indices are suppressed until needed. Finally, MLES is minimal in the sense of having the fewest vevs consistent with data: $\langle h_1 \rangle = v_1, \langle h_2 \rangle = v_2$ and all others vanishing.

Given the above minimality of MLES, it is not surprising that it should receive the most attention. However, from the theoretical viewpoint it does not have a unique minimality, even when we restrict our attention to models with minimal field content. This is because gauge invariance allows

$$f_{\Delta L} = Q\lambda D^c L + L\lambda' E^c L + \mu' L H_2 \tag{3a}$$

and

$$f_{\Delta B} = \lambda'' U^c D^c D^c, \tag{3b}$$

which, if present, would give the proton a weak decay rate. It is necessary to impose some symmetry to remove the interactions of (3a) or (3b). There are four ways of doing this: (3a) may be removed by imposing L, (3b) by imposing B, and both by imposing a Z_2 symmetry (R_p) or a Z_N symmetry ($N > 2$). R parity, R_p, is a multiplicative parity which is $+1$ on all particles and -1 on superpartners. In the case of the MLES model, this is equivalent to matter parity, which changes the sign of all matter superfields. It was originally imposed, in its present form, as a convenient way of constructing a realistic supersymmetric $SU(5)$ grand unified theory.[6] However, different unified schemes lead to all of the above four cases, and, hence, from the theoretical viewpoint it is difficult to justify a clear preference of one case over the rest. In addition there is the question of whether a sneutrino vev might occur in the R_p invariant case.

If the alternatives to R_p invariance are simply ignored, a convincing argument gives missing energy as a good signature for supersymmetry at colliders. Proton stability leads to R_p invariance which implys the stability of the lightest superpartner (LSP). Cosmology requires the LSP to be neutral and, since its interactions with matter are therefore weak, superpartner pair production at colliders will lead to missing energy signatures. The problem with this litany is that it ignores the alternatives to R_p invariance. These alternatives typically do not lead to events with large missing energy, but have their own distinct and characteristic signatures.

I have recently reviewed the status of these models,[7] and last year I lectured here on the exciting collider signatures from the models with B and L violation.[8] This year I will bring you up to date on some more recent developments which have been triggered by the Z data from LEP.

As a prelude, and in case you think supersymmetric model building is a closed subject, let me enumerate the problems encountered by weak scale supersymmetry.

1. Renormalizable B and L violation. The interactions of equations 3 are a major embarrassment. Supersymmetry appears to lead us backwards. At least it forces us to extra symmetries.

2. There is the problem of predictivity. Supersymmetry is justly accused of fitting all data and wriggly out of all constraints. While supersymmetric superpartner interactions do not introduce additional parameters beyond those of the standard model, many extra parameters appear when supersymmetry breaking is included. In the case of breaking supersymmetry in $N = 1$ supergravity models, and imposing the most stringent constraints on the theory at the Planck scale, six new real parameters appear. Renormalized at the Planck scale these are (see equation 2)

i) a degenerate Majorana mass for all gauginos, $\widetilde{m}$

ii) a degenerate mass for all scalars, m^2

iii) a trilinear scalar interaction between squarks and Higgs $|A|e^{i\phi_A}$

iv) a bilinear scalar-scalar mass $(h_1 h_2)|B|e^{i\phi_B}$

3. The weak scale problem. Lets suppose that supersymmetry somehow dynamically generates $\widetilde{m}$ and m to be of order the weak scale. While it is true that renormalization of the Higgs mass squared leads to a very elegant understanding of $SU(2) \times U(1)$ breaking, there is the question of the supersymmetric parameter μ of equation 1. In the context of the MLES model it is just put in by hand to be of order the weak scale, and this ruins claims to have understood the weak scale. If μ were of order M_p there would be no light Higgs. If μ were absent the form of the supergravity potential forces B to zero, and this ruins electroweak symmetry breaking. This problem has been solved in several ways by complicating the model. None of the problems I am discussing is a true disaster for weak scale supersymmetry. Nevertheless, together they may indicate that MLES is badly off track, and may need radical modification.

4. Ultimately the question of weak scale supersymmetry will be settled experimentally. Experiments over the next decade will teach us a great deal about physics at the TeV scale. However, from this viewpoint I believe that MLES

is very awkwardly formulated. It is formulated in terms of some very technical assumptions about the form of the interactions in the $N = 1$ supergravity model at the Planck scale. The reason for this is that when it was formulated theorists were eager to find an elegant understanding for the origin of supersymmetry breaking. However, this formulation is now problemmatic: if experiments exclude MLES we will learn that this particular supergravity method for breaking supersymmetry is not correct. We will not settle the issue of weak scale supersymmetry. Recently, Lisa Randall and I have formulated weak scale supersymmetry purely in terms of assumptions about physics at the weak scale.[9] We can and should test physics at the weak scale. I will give an example of such a formulation later with the $U(1)_R$ invariant model.

5. In the MLES model a one loop diagram involving either ϕ_A or ϕ_B leads to an electric dipole moment of the quark.[10] In order not to give too large a neutron electric dipole moment these phases are then constrained to be small: $\phi_{A,B} \lesssim 10^{-2}\left(\frac{m_{susy}}{300GeV}\right)^2$. It is not easy to come up with reasons for A and B to have small phases. Of course, numerically the problem is not nearly as bad as the strong CP problem.[11] There are two loop contributions to the CP violating operator $G^2\widetilde{G}$[12] (G is the QCD gluon field strength tensor) which earlier this year looked like constraining ϕ_A to be less than about 10^{-6}. However, an anomalous dimension enhancement sign error had overestimated the effect by 5.10^4. The resulting effect of the operator $G^2\widetilde{G}$ in supersymmetry is less constraining than the electric (and color electric) dipole moment quark operators by about a factor of 10.[13]

One frustration of low energy supersymmetry is that there is any need for a Higgs multiplet at all. The sneutrino has exactly the quantum numbers of the Higgs! However, if the sneutrino is the sole origin of electroweak breaking the corresponding neutrino and charged lepton get large Dirac masses from $\langle\tilde{\nu}^*\rangle\widetilde{Z}\nu$ and $\langle\tilde{\nu}\rangle^*\tilde{w}\ell$. However, it has been pointed out that in the context of the MLES model the tau sneutrino may acquire a vev as well as the two Higgs doublets, provided one studies the $\mu \to 0$ limit.[1] In this case the physical light tau doublet can be identified as $(\cos\theta\ \nu_\tau + \sin\theta\widetilde{H}, \cos\theta\ \tau + \sin\theta\widetilde{H}^-)$ where θ is a mixing angle which depends on the vevs. This model is interesting for several reasons.

1) The model shows that R parity may be broken even in MLES. This breaking leads to crucial changes in experimental signatures and cosmology.

2) The tau sneutrino vev can easily be triggered by the vevs v_1 and v_2 because the scalar potential contains the D terms: $g^2(h_1^* h_1 - h_2^* h_2 + \nu^* \nu)^2$ and a heavy top quark implies $v_2 > v_1$.

3) Since $\mu = 0$ the model does not require an understanding of why this parameter is of order M_W.

4) Since $\mu = 0$ the model has a higher degree of predictivity that the MLES model. The chargino mass matrix is particularly constrained. Also there is a very light neutralino state $\nu_\perp$, in addition to the three neutrinos.

In fact Z decay data can now exclude this model.[14] The neutralino, chargino, gluino masses are determined in terms of three parameters: $\widetilde{m}, \sqrt{v_1^2 + v_\tau^2}$ and v_2. Furthermore $\sqrt{v_1^2 + v_2^2 + v_\tau^2} = 250$ GeV so that there are two free parameters remaining, which I take as $\widetilde{m}$ and $\tan\beta = v_2/\sqrt{v_1^2 + v_\tau^2}$. Figure 1 illustrates the processes which rule out this model in the various regions of parameter space. In region i) there is a chargino light enough to be pair produced in Z decay. Although $\widetilde{m}$ is large, the chargino is light because of a see-saw mechanism. In region ii) the rate for $Z \to v_\perp v_\perp$ is sufficient to give too large a contribution to the invisible Z width. This decay rate depends on tanβ because $v_\perp$ is a superposition of $T_3 = +1/2$ and $-1/2$ components. For $\tan\beta = 1$, the $Z v_\perp v_\perp$ coupling vanishes. In region iii) there is an off diagonal coupling $Z v_\perp \chi$ where χ is another neutralino lighter than the Z. It's decay leads to $\bar{b}b+$ missing signatures. These events are similar to those excluded by the Higgs search.

As a second illustration I consider a model proposed recently by Lisa Randall and myself.[2] The idea is to produce as predictive a model of supersymmetry as possible by promoting R parity to a continuous $U(1)_R$ symmetry. In many ways the model is the most elegant model of supersymmetry that I have seen, although I am biased of course. In particular the five problems of the MLES model discussed above are all solved. The $U(1)_R$ symmetry is defined as follows:

All standard model particles:	charge 0
Left handed Higgsinos:	charge -1
Left handed gauginos :	charge +1
Squarks and sleptons (defined as partners of left handed quarks, antiquarks, leptons and anti-leptons):	charge +1

The theory at the weak scale is the most general model with broken supersymmetry which has

A) no quadratic divergences

B) all flavor violation in the usual three Yukawa matrices

C) gauge symmetry $SU(3) \times SU(2) \times U(1)$ and global symmetry $U(1)_R$.

D) minimal fields consistent with A) —C). Since $U(1)_R$ is never broken superpartners must be pair produced, and as for MLES, the lightest is stable.

This model solves the five problems of MLES as follows

1. All the B and L violating interactions of equation 3 are forbidden by $U(1)_R$.

2. The soft parameters $\widetilde{m}, |A|, \phi_A$ are set to zero by $U(1)_R$. Also $\mu = 0$ and ϕ_B is non physical and can be rotated away by a $U(1)_{PQ}$ rotation. The removal of these five parameters leads to a wide set of predictions. In particular it is obvious from the R charges that fermionic superpartners can never acquire Majorana masses. The only allowed masses are Dirac couplings of gauginos to Higgsinos.

3. Since $U(1)_R$ forces μ to vanish, there is no problem in understanding why μ should be of order M_W. Note that it is because (A) allows the most general set of soft operators, not necessarily just those which come from a minimal $N = 1$ supergravity scenario, that B can be non-zero even when $\mu = 0$.

4. From the nature of the assumptions A) —D) it is clear that this model is formulated at the weak scale. The technical assumptions about $N = 1$ supergravity have been replaced by the mild constraints A) and B). If A) is false there is little motivation for weak scale supersymmetry, while if B is false GIM violation is likely to be problematic

If the model is proved false we learn something about weak scale physics. Some of A) — D) must be wrong. The theory may or may not have a supergravity origin.

5. Since $\phi_A = \phi_B = 0$ there are no one loop diagrams for the neutron electric dipole moment.

Honesty compels me to mention that these problems have been solved at the expense of one new problem: the gluino is massless. This necessitates introducing an extra chiral superfield which is a color octet $(0,\tilde{0})$. The most general soft operators then include the mass term $\tilde{g}\tilde{0}$.[2] Although unpleasant, the positive features of R invariant supersymmetry easily justify its exploration.

The two most exciting predictions are for the electroweak gaugino masses and for the lightest Higgs mass. Since $\mu = \widetilde{m} = 0$ the electroweak gauginos only acquire mass from electroweak symmetry break. The $\tilde{Z}$ marries $\widetilde{H}_Z = \cos\beta\widetilde{H}_1^0 - \sin\beta\widetilde{H}_2^0$ to become a neutral Dirac fermion of mass M_Z. The photino and $\widetilde{H}_\gamma = \cos\beta\widetilde{H}_2^0 + \sin\beta\widetilde{H}_1^0$ are massless at tree level, and acquire a Dirac coupling of about 1 GeV at one loop. There are two Dirac charginos one heavier and one lighter than the W: $\tilde{w}^-\widetilde{H}^+$ has a mass $\sqrt{2}\sin\beta M_W$ and $\tilde{w}^+\widetilde{H}^-$ a mass $\sqrt{2}\cos\beta M_W$. We follow the usual convention that $\tan\beta = v_2/v_1$. The light Dirac $\tilde{\gamma}\widetilde{H}_\gamma$ can be produced in Z decay with a width $|\cos 2\beta|^2$ compared to that of a neutrino. Hence the model increases the number of neutrino species measured in Z decay:

$$\Delta N_\nu = |\cos 2\beta|^2. \tag{4}$$

The potential for the two Higgs doublets h_1 and h_2 is the same as for the MLES model. Hence the Higgs mass relations of that model apply also to the present model. In particular one Higgs is lighter than the Z:

$$m_h < M_Z|\cos 2\beta|. \tag{5}$$

Furthermore we know from (4) that $|\cos 2\beta|$ is quite small, and in this limit h has couplings to the fermions which are the same as the Higgs of the standard model.

In figure 2 I illustrate how the Z decay data on ΔN_ν and m_h has rapidly constrained this $U(1)_R$ invariant model. Before LEP it was essentially unconstrained. The 1989 LEP data led to a considerable constraint, but left a sizable allowed region. The data announced in June at the $\nu - 90$ conference has now excluded the model at the 2σ level. This is a powerful illustration of how LEP is bringing us to a new era of understanding of physics at the weak scale.

I conclude with three points:

1) It seems to me unreasonable that the standard model with a single Higgs boson is the whole story for weak scale physics. The weak scale, like all other masses in physics, needs a protection mechanism.

2) Ideas for the protection mechanism, technicolor and supersymmetry for example, are being increasingly constrained by collider data.

3) Could there be an alternative to dimensional transmutations?

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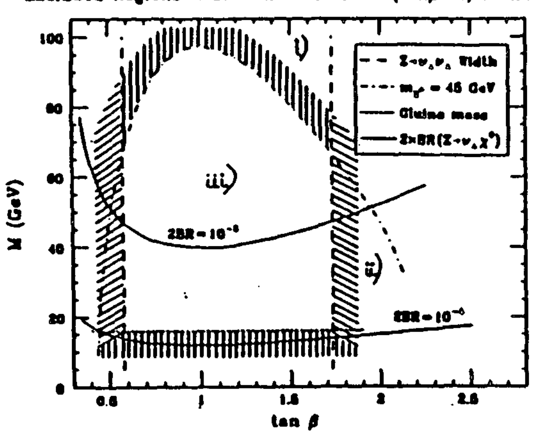

Figure 1: Excluded Regions & BR Contours in the $(\tan\beta - M)$ Plane

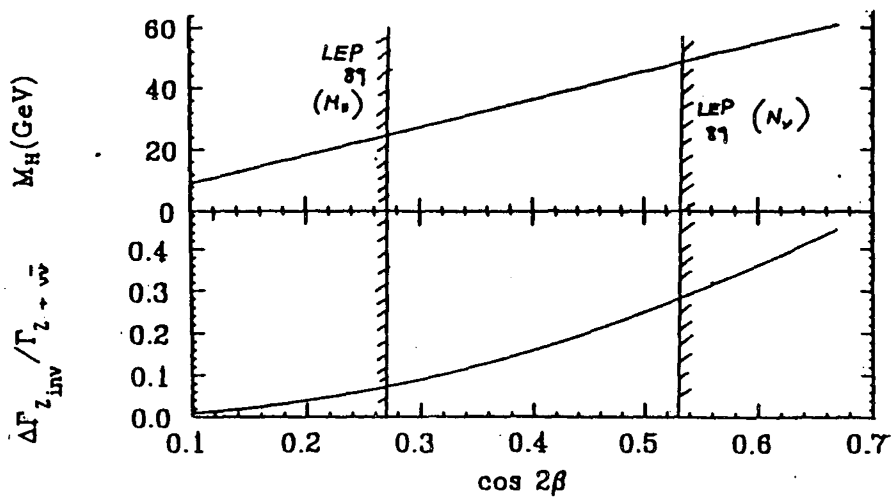

Figure 2: Constraints on $\cos 2\beta$ from Higgs mass and width of Z to invisibles.

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