Is the World Supersymmetric? Do We Already Know?

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Abstract

In addition to the very good theoretical motivations for supersymmetry, there are now at least nine phenomenological indications that nature is supersymmetric. All are indirect, so more is better. They are enumerated here. Some discussion is also given of models, of when and where superpartners might be directly detected, and of why the scale of supersymmetry cannot be pushed up if superpartners and SUSY Higgs bosons are not directly detected.

*Based on Invited Talks at the Coral Gables Conference on “Unified Symmetry in the Small and in the Large”, Jan. 1993, and at the XVIII Rencontres de Moriond, Les Arc, March, 1993.*
INTRODUCTION

It is widely accepted that new physics, beyond the Standard Model (SM), will be discovered even though the SM successfully describes experiments. Reasons for believing there will be new physics fall into at least four categories: regularities not explained by the SM, such as $Q_p = -Q_e$, the similarity of quark and lepton spectra, mass relations such as $m_b = m_\tau$ at the GUT scale, the unification of gauge couplings at the GUT scale, etc.; dynamical questions such as the origin of mass and the hierarchy of masses; “why” questions such as why three families, why $SU(3) \times SU(2) \times U(1)$, why is parity violated; and connections to gravity and the cosmological constant problem. Some might include as an additional category the tantalizing properties of some ambitious theories that include possible answers to some of the above questions, or promising approaches to them.

Given that new physics will occur, one might wonder if we already have clues to what the new physics is. Can we work it out without needing to see it explicitly? Physicists are supposed to be good at indirect reasoning.

Of the alternatives that have been considered probably the largest number of theorists expect nature to be supersymmetric, but theoretical prejudices do not have a great record of being right. The theoretical motivations for supersymmetry, particularly the connection to gravity and the ability to maintain two widely separated scales, are powerful but do not guarantee that nature is supersymmetric.

I believe that in the past two years indirect evidence for supersymmetry has been accumulating. There are now at least nine phenomenological indications, i.e., phenomena that are predicted by or consistent with supersymmetry but would not have been if some data had been different. Five are things that happen and four are things that do not happen.

Since these constitute indirect evidence, more is better. Obviously any single indirect piece of evidence cannot uniquely point toward supersymmetry. Once superpartners are found it will not require special cleverness to accept supersymmetry. It is more fun to get it right ahead of the direct evidence. So the familiar (Feynman?) remark that one good argument is better than several bad ones not only does not apply here, it is misleading. Indeed, anyone who would prefer “one good argument” should pause and ask whether there is any indirect argument that would convince them.

A number of groups of people have been studying models that increasingly build in theoretical and phenomenological constraints. I will not review these here, but it is relevant to know that one can construct real models that exhibit all of the properties described below. Groups studying models include R. Arnowitt and P. Nath; R. Roberts and G.G. Ross; J. Lopez, D. Nanopoulos, A. Zichichi, H. Pois et al.; J. Hagelin, S. Kelley et al.; J. Ellis, F. Zwirner et al.; G.L. Kane, Chris Kolda, L. Roszkowski, James Wells; R. Barbieri et al.; P. Langacker et al.; Q. Shafi et al.; T. Yanagida, H. Murayama et al.; M. Carena, C. Wagner, S. Pokorski.

The spirit in which this talk is offered is to encourage more people to take supersymmetry more seriously. Whenever a large number of good physicists have taken a topic seriously and focussed on it, progress has been rapid. There is much need for theoretical work to improve the formulation of the theory at the electroweak scale, and to study how supersymmetry is broken. Experimenters could increase priorities for direct and indirect searches motivated by supersymmetry predictions, and pay particular
attention to sensitivity to supersymmetry triggers and signatures.

None of the following indications are unique — each could have an alternative interpretation. Taken together, they relate a large amount of beyond-the-SM physics. No other approach comes close to such achievements. In fact, other approaches may be most valuable to show that it is easy to get wrong the things that supersymmetry gets right. Perhaps a conservative view is that the items below are all tests of any approach to physics beyond the SM.

All of the indications discussed below have also been remarked on by others. This is a review talk, bringing these points together. It is also important to be sure that all of these effects can occur in one consistent model. The whole is greater than the sum of the parts.

THINGS THAT HAPPEN

A. It is now familiar to everyone that as the precision of measurement of the gauge couplings at $m_Z$ improved, the gauge couplings still could be unified at a scale we can call the GUT scale, about $10^{16}$ GeV, in a supersymmetric theory. Although there is another parameter in a supersymmetric theory (the scale of superpartner masses), it is not arbitrary — unless it is between about 0.1 TeV and 1 TeV it is not the supersymmetric theory of interest. It comes out right. Unification of the three gauge couplings does not occur at all in a non-SUSY $SU(5)$ GUT. It occurs in some other theories, but only if an intermediate scale is added. Our version of the curves is shown in Fig. 1.

B. It was pointed out in ref. 4 that independently the coming together of $m_b$ and $m_\tau$ at the GUT scale occurred in the SUSY case and not in the non-SUSY case. Our version of this is also shown in Fig. 1. What is significant is that $m_b = m_\tau$ at the same scale where the gauge couplings meet, within experimental errors. Given the apparent unification of forces, and the apparent similarity of quark and lepton spectra, it would be courageous to claim this result is an accident.

C. It was noticed a decade ago that if $m_{top}$ were large enough (somewhat above $m_W$), then the Higgs mechanism occurs automatically in a supersymmetric theory, rather than having to be an ad hoc add-on as in the SM. $m_{top}$ is indeed that large. This is a beautiful result. The coefficient $m^2_{ht}$ of the quadratic term in the scalar potential for the scalar field coupled to up-type quarks goes negative and triggers the Higgs mechanism. The weak scale is determined by where $m^2_{ht}$ goes negative, and in the same models that give Fig. 1 (and other quantitative results described below) this occurs in such a way that $m^2_Z$ can be fitted accurately. While parameters are adjusted to get $m^2_Z$ right, there is no fine tuning if the SUSY mass parameters are well below 1 TeV.

Fig. 2 shows how this happens, and shows the SUSY spectrum in one model. At the GUT scale the masses have a simple pattern. At the weak scale they are calculated to have other values. One (mass)$^2$ of a scalar goes negative, the one whose renormalization group equation contains a large negative term from the top quark Yukawa coupling (imagine the (mass)$^2$ as running from the GUT scale down).

D. While discovery of a light Higgs boson would not convince everyone that nature is supersymmetric, it would satisfy most. Global analyses of the precision measurements
from LEP and FNAL have typically shown a mild preference for a light Higgs boson when analyzed as functions of $m_{t\bar{t}}$ and $m_h$. For our purposes “light” could be any $m_h < 1$ TeV; once a Higgs boson exists, in a world with a high scale where the theory remains perturbative between the high scale and the weak scale, theorems require $m_h \lesssim 170$ GeV in the SM and $m_h \lesssim 146$ GeV for SUSY, for the relevant region of $m_{t\bar{t}}$. A and B above show that the existence of the high scale is now no longer a matter of taste.

The relevant analysis of the data to decide if the precision measurements provide evidence for a light Higgs boson is not the two variable one, but one where $m_{t\bar{t}}$ is fixed. Let us assume the candidate events being observed at FNAL will indeed eventually lead to reporting the detection of $m_{t\bar{t}}$. Then from the integrated luminosity taken by the detectors, and the published cross section, one would guess $m_{t\bar{t}} \cong 135$ GeV, a value fully consistent with the LEP data (remember, if one is testing the hypothesis of a light Higgs one should use the LEP data analysis with $m_h \cong m_Z$). Once $m_{t\bar{t}}$ is fixed at such a value, one finds that the data prefers a “light” Higgs boson at the level of several standard deviations.

When analysis of the data now in hand at LEP is completed this result should become firmer if we are not being fooled by statistical or unknown systematic effects. And soon the detection (and mass) of top should be settled if indeed $m_{t\bar{t}} \sim 135$ GeV. Until then, we can tentatively conclude that there is mild evidence for the existence of a Higgs boson, which can be interpreted as evidence for supersymmetry.

E. The final thing that “happens” is the dark matter. It has been understood for a decade that the LSP will normally be stable, and will automatically be a good candidate for cold dark matter. As constraints from theory and data have increasingly been imposed this has continued to be true. It is phenomenologically non-trivial; for example, the lightest sneutrino is excluded as a dark matter candidate but the lightest neutralino behaves just right, giving $\Omega \sim 1$; the LSP with the right properties is mainly gaugino.

One might ask “what about R-parity violation that could make the LSP unstable”? Eventually phenomenological constraints may be able to show that R-parity conservation is valid, or sufficiently valid to give LSP’s lifetimes larger than the age of the universe. In some theories R-parity conservation is natural. But I think the right answer to this question is that supersymmetry automatically provided a dark matter candidate with certain properties and this turned out to be the kind of dark matter needed by cosmology and astrophysics. In the context of the present analysis it is appropriate to presume this is no accident; thus R-parity is conserved. In supersymmetric grand unified theories in general $\nu$ masses will exist, and perhaps also pseudo-Goldstone bosons from breaking of global symmetries, so that other forms of dark matter will also exist. As we learn more about the theory, the ratios of the contributions to $\Omega$ of the different forms will be calculated.

**THINGS THAT DON’T HAPPEN**

F. Given the unification of forces, and $m_b = m_\tau$, we expect some kind of quark and lepton unification, and it is likely that protons will be unstable. Then it is well established that proton decay is too rapid in some theories including an $SU(5)$ GUT,
but in a supersymmetric GUT the proton lifetime is OK. This happens in part because the extra particle content of the supersymmetric theory moves the GUT scale higher and the lifetime scales as $m_{GUT}^4$, but it is more complicated because the dominant operators change. Typically models give a range of parameters for which the lifetime is OK, and a range for which it is not, a nice situation because it suggests that experiments may be on the edge of detecting a result.

G. It is well known that the precision measurements from LEP and FNAL are well described by the SM if $m_{top}$ and $m_h$ are in certain ranges. People have for several years looked for the effects of physics beyond the SM, in hopes that a clue would appear or that some ideas would be constrained. It is also well known that some models indeed can give predictions in conflict with the data — most simply, a degenerate quark doublet gives a contribution $+1/2\pi$ to the observable $S$, whose central value is somewhat negative; and perhaps TC theories are inconsistent with the data. My point is not to argue one way or the other about TC, but to point out that in the case of supersymmetry the agreement with the precision measurements is, if anything, better than for the SM. For much of the parameter space the region predicted by SUSY and the $2\sigma$ experimental region lie on top of each other. The point of mentioning the other models is simply to show that this is a non-trivial success.

H. It has been known for a decade that supersymmetric theories could give large flavor changing neutral currents (FCNC) and induce $K^0 - \overline{K^0}$ mixing, $B^0 - \overline{B^0}$ mixing, $K_L \rightarrow \mu e$, etc. Such effects can be a major problem for other kinds of beyond-the-SM-physics. What happens in supersymmetric models is that any model where the down-type squarks are nearly degenerate at the GUT scale, and their splitting at the weak scale arises from running their masses to the weak scale, automatically satisfies FCNC constraints. This is “natural”, in the sense that once the sfermions are approximately degenerate at the high scale, this degeneracy is preserved by radiative corrections. Thus the smallness of FCNC can be viewed as a success of SUSY.

I. In a supersymmetric theory the mass of the lightest Higgs boson is calculable if the soft-breaking parameters are known, and it depends on the same parameters as the superpartners. In constrained models it is never very light. In addition, the one-top-loop radiative corrections shift $m_{h^0}$ up by $\sim 10$ GeV. In practice $m_{h^0}$ is usually in the range 70-110 GeV in models. So if a light $h^0$ had been found at LEP already it would have been very difficult to make it consistent with a supersymmetric world in which the other good features listed in this talk were maintained simultaneously.
WHEN, WHERE MIGHT SUPERPARTNERS OR SUSY HIGGS BE DETECTED?

This question is best studied with models, and such studies are in progress by the groups mentioned in the introduction. It is a complicated and subtle task to incorporate all of the theoretical and experimental constraints into models. Progress is being made, though the results of all groups are not yet consistent. It is remarkable that fully detailed models can indeed be constructed. In the next few months studies of models are likely to converge to a fairly small region of allowed mass ranges.

At LEP there is a window for the lightest SUSY Higgs boson. Typically in models it ranges from 70 GeV to 110 GeV. There is an upper limit of about 146 GeV (see next section), but the upper limit is seldom saturated in models. LEP also has a window for the lightest chargino. Dark matter constraints suggest sleptons may be beyond the reach of LEP200.

At FNAL the decay \( t \rightarrow bH^+ \) can occur for a small region of parameter space. For higher luminosities production of gaugino pairs is detectable in lepton channels. Over some of parameter space the squarks and gluinos can be detected. Particularly at larger luminosities there is a significant window.

SSC and LHC will be supersymmetry factories that will permit the detection and study of much of the spectrum, given appropriate detectors. Careful study of neutralinos and charginos, and detection of sleptons and sneutrinos, may require NLC, which can do very useful analyses, particularly with a polarized beam.

Models show clearly that superpartner masses fall naturally in regions such that we would have been very lucky if a superpartner or SUSY Higgs boson had been detected so far. For LEP200, or FNAL with the main injector, a little luck is still required. Detailed results will be reported in ref. 3, and have already been given for some cases by several groups of authors listed in the introduction. Although sometimes people have mentioned the absence of superpartners as an argument against supersymmetry, it is clear that constrained model studies require superpartners typically heavier than \( m_W \).

CAN THE MASSES OF SUPERPARTNERS AND SUSY HIGGS BE PUSHED UP IF THEY ARE NOT DETECTED?

What if superpartners or a light Higgs boson are not detected? Can supersymmetry be excluded, or will it just be pushed to a higher scale? The answer is that it can be tested definitively. There are three relevant points; (i) refers to the lightest Higgs boson and (ii) and (iii) to superpartners.

(i) It has been possible to show that there exists an upper limit on the mass of the lightest Higgs boson in any supersymmetric theory. [“Any” could include extensions of the Higgs sector, the low energy gauge group, and the spectrum of heavy fermions. The limit exists including all of these.] Its value has been calculated (within a few % accuracy) if the low energy gauge group is the SM one: it is 146 GeV for \( m_{\text{top}} > 100 \text{ GeV} \). [Additional heavy fermions could increase this as much as 12 GeV per family; other constraints suggest at most two such families could exist. Most likely no additional fermions exist. If the gauge group is larger I think the upper bound turns out to be lower, but that is not proved...}

...
(ii) There are two kinds of arguments that superpartner masses cannot be pushed up. Today both can be barely evaded by unpleasant fine-tunings, but it seems likely that continued study of models and constraints will sharpen this situation.

One argument is that unless some slepton or squark is light enough (a slepton in models) there will be too much dark matter, and the universe will be overclosed. The LSP's are in equilibrium with other particles in the early universe. They can annihilate by sfermion exchange ($\tilde{f}$) to final fermions ($\text{LSP} + \overline{\text{LSP}} \rightarrow f + \overline{f}$), or via an s-channel $Z$, $\text{LSP} + \overline{\text{LSP}} \rightarrow Z^{(*)} \rightarrow f + \overline{f}$; other final states are typically less important. Since the $Z$ couplings are neutral current ones, giving small rates, except for special choices of the LSP wave function (mainly Higgsino LSP’s since $\gamma$ and $B$ do not couple to $Z$, and such LSP’s are disfavored) the annihilation through $Z$ is too small to avoid giving $\Omega > 1$. If sfermions are too heavy, the annihilation rate by sfermion exchange will be too small to bring $\Omega$ to unity. Numerically, sleptons below about 400 GeV are needed. Since most superpartner masses are tied together, this implies most of the superpartners will be light enough for SSC/LHC to detect. Note that this argument does not require a commitment to how much dark matter is due to the LSP, but only that the dark matter does not overclose the universe.

(iii) The second kind of argument is based on models. Basically, satisfying the theoretical and experimental constraints always produces a spectrum that is at least in part detectable at SSC/LHC. A recent analysis found upper limits on all superpartner masses without requiring fine-tuning constraints; all masses were well within the SSC/LHC range. It is possible that in the near future combining a number of constraints will allow a firm upper limit to be set on superpartner spectra from acceptable supersymmetric theories.

ACKNOWLEDGEMENTS

I appreciate comments and assistance from C. Kolda, J. Wells, L. Roszkowski, H. Haber, M. Dine and D. Kennedy.
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Figure 1 shows the running of the gauge couplings\(^{(1,4)}\) \((\alpha_i^{-1})\), and independently of the masses\(^{(4)}\) \(m_b\) and \(m_\tau\), in theories with supersymmetric RGE’s. The left scale is for \(m_b, m_\tau\) and the right scale for \((\alpha_i^{-1})\). The band for \(m_b\) is determined by the uncertainty in extracting \(m_b\) from data. Note that both come together at the same high scale.

Figure 2 shows the spectrum of one model where there is a simple spectrum at the GUT scale, and different superpartner masses are generated at the weak scale by radiative effects. Colored superpartners automatically get heavier so color symmetry cannot be broken. One Higgs field (mass)\(^2\) goes negative and produces the Higgs mechanism as a consequence of the structure of the supersymmetric theory. For that field what is shown is \(-|m_{h_i}^2|^{1/2}\).