TESTS AND IMPLICATIONS OF INCREASING EVIDENCE FOR SUPERPARTNERS

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Abstract

Although no individual piece of experimental evidence for supersymmetry is compelling so far, several are about as good as they can be with present errors. Most important, all pieces of evidence imply the same values for common parameters — a necessary condition, and one unlikely to hold if the hints from data are misleading. The parameters are sparticle or soft-breaking masses and \( \tan \beta \). For the parameter ranges reported here, there are so far no signals that should have occurred but did not. Given those parameters a number of predictions can test whether the evidence is real. It turns out that the predictions are mostly different from the conventional supersymmetry ones, and might have been difficult to recognize as signals of superpartners. They are testable at LEP2, where neutralinos and charginos will appear mainly as \( \gamma \gamma^+ \) large \( \mathcal{E} \) events, \( \gamma^+ \) very large \( \mathcal{E} \) events, and very soft lepton pairs of same or mixed flavor. The results demonstrate that we understand a lot about how to extract an effective SUSY Lagrangian from limited data, and that we can reasonably hope to learn about the theory near the Planck scale from the data at the electroweak scale.

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Introduction

Supersymmetry can allow a solution of the hierarchy problem, unification of the Standard Model forces, unification of the Standard Model forces with gravity, provide a derivation of the Higgs mechanism (which led to the prediction that $M$ would be large), and provide a cold dark matter candidate, the lightest superpartner (LSP).

If string theory is relevant to understanding weak scale physics in detail it probably implies supersymmetry at the weak scale.

In this talk I will not emphasize these kinds of evidence for supersymmetry in nature. Rather I want to focus on more explicit hints of effects of superpartners. What would be nice, of course, is a clear, explicit, unambiguous effect. But a little reflection implies that such an obvious effect is unlikely. There are two ways effects of supersymmetry can appear. Superpartners can be pair-produced as energy or luminosity is increased at LEP or the Tevatron colliders. Once the energy threshold is crossed, luminosity is the important consideration. That necessarily means that events will initially appear in small numbers. Further, because every superpartner will decay into Standard Model particles plus an escaping LSP, and superpartners will be pair-produced, no event will show a high resolution mass peak or be uniquely identifiable, as $Z \rightarrow \ell^+ \ell^-$ was or even $W^\pm \rightarrow \ell^\pm \nu$ with only one escaping particle. A cursory study of existing limits shows that we would have been lucky to have observed any superpartners so far. Most published limits depend on extra assumptions, so generally valid limits are even fewer than reported ones.

The second way effects could appear is as loop contributions in rare decays or as small radiative corrections to branching ratios. The most likely place for an effect has been known for over two decades to be $BR(b \rightarrow s\gamma)$ both because there is no tree level contribution so the superpartner loop can be of the same order as the Standard Model loop, and because in the supersymmetric limit the superpartner and Standard Model contributions must cancel coherently to give a vanishing decay. But if the supersymmetric effect is (say) $\sim 30\%$ (quite large), to be statistically significant the errors have to be $\lesssim 10\%$. The theoretical error in the Standard Model value has recently decreased to this level after much difficult effort, so finally an effect here will eventually be possible to observe. The present experimental error is about $20\%$ of the Standard Model value so that has to decrease too; new data will be reported eventually by the CLEO collaboration starting spring or summer of 1997.

The other place where supersymmetric loop effects were predicted to be observable was $R_b = BR(Z \rightarrow b\bar{b})/BR(Z \rightarrow \text{hadrons})$. The recent history here has been complicated. A few years ago a large deviation was reported at LEP, leading to renewed theoretical study — the calculations are complicated. The first theoretical studies showed that effects almost as large as the reported deviations from the Standard Model (then $\sim 2\%$) could be obtained. Then constraints from other data were put in, and the possible size of the theoretical effect decreased to a maximum of about $1\%$, with a typical value of about $0.65 \pm 0.2\%$. At the same time reevaluations of the experimental effect gave a decreasing one. The current world average is
0.2178 ± 0.0011 compared to a Standard Model value of 0.2158, while the average of four measurements reported in the past year is 0.2159 ± 0.0014, OPAL 0.2178 ± 0.0022, and DELPHI 0.2179 ± 0.0039. The experiments are very difficult. The bottom line is that by itself $R_b$ cannot be strong evidence for or against a significant supersymmetric effect from the constrained theory of order $\frac{2}{3}\%$ since the experimental 1σ error is of that order.

Fortunately, as we will see below, supersymmetry affects $BR(b \to s\gamma)$ and $R_b$ in a coordinated way, so when they are combined the $R_b$ data can still play a useful role. There is an additional test from the value of $\alpha_s$. But the net effect cannot be compelling.

In the past two years several weak hints of supersymmetry have emerged, and I will briefly describe them below. Each hint can only be interpreted as evidence for supersymmetry if certain parameters take on certain values. The parameters we need to discuss these issues are $\mu$ (which can be thought of as an effective higgsino mass, $-M_{\text{Planck}} \lesssim \mu \lesssim M_{\text{Planck}}$), $M_1$ and $M_2$ ($U(1)$ and $SU(2)$ gaugino masses ($0 \lesssim M_1, M_2 \lesssim \text{TeV}$)), $\tan \beta$ (ratio of the two vacuum expectation values, $1 \lesssim \tan \beta \lesssim 70$), $M_{\tilde{t}_1}$ (mass of the light stop mass eigenstate), and $\theta_{\tilde{t}}$ (a rotation angle from symmetry eigenstates to mass eigenstates that measures how much of $\tilde{t}_1$ is $\tilde{t}_R$ or $\tilde{t}_L$, the superpartners of $t_R$ or $t_L$). The full theory has many more parameters that will come into play after more superpartners are observed, but these few are all we need for the present. These parameters determine the masses and coupling of neutralinos and charginos. The notation here is that $\tilde{N}_i$ represent the four neutralino mass eigenstates, linear combinations of the superpartners of $\tilde{\gamma}$, $\tilde{Z}$, $\tilde{h}_U$, $\tilde{h}_D$, and $\tilde{C}_i^\pm$ the two chargino mass eigenstates, linear combinations of the superpartners $\tilde{W}^\pm$ and $\tilde{H}^\pm$. $\tilde{N}_1$ is the LSP.

If we were being fooled by fluctuations in data, and the various hints were not actually evidence for supersymmetry, we would expect that measurements of $\mu$ or $\tan \beta$ or other parameters would give one value from one bit of evidence, a second value from another bit, and so on. Since the allowed ranges are large it would be surprising if different (misleading) data gave similar values. What is exciting is that all the evidence leads to a common set of values for $\mu$, $\tan \beta$, $M_1$, $M_2$, and $\tilde{t}_1$! It is this emergence of a common set of parameters that is the strongest evidence for supersymmetry today. It is reminiscent of the testing of the Standard Model by checking whether different experiments gave a common value of $\sin^2 \theta_W$. Figure 1 summarizes the parameters implied by taking the SUSY clues seriously, and gives a set of “models” that are consistent with all reported data. (The word “models” is used loosely both for the general class studied here, with a neutralino LSP that is mainly higgsino, and for particular correlated sets of parameters in the ranges described in Figure 1.) Once we have a common set of parameters we can make a number of predictions. We will see that several are non-standard SUSY predictions, mainly for LEP.

The entire analysis described here is done with an effective Lagrangian at the EW scale, the most general softly broken supersymmetric Lagrangian. No unification
Figure 1: Figure 1 shows the existing clues that hint at evidence for superpartners. None are compelling, though each is about as strong as it could be given present errors and integrated luminosities. If they were not evidence for superpartners, each might have faked such evidence, but it is extremely unlikely all would have worked and given the same result for $\tan \beta$, $\mu$, $M_1$, $M_2$, $\tilde{t}_1$. Each is described in the following sections.

The region of SUSY parameter space in the inner circle is consistent with having the indicated phenomena as signals, and with all collider and decay constraints. The LSP is mainly higgsino with mass about 50 GeV.
assumptions are made for soft-breaking masses, and no assumptions about SUSY breaking. The data force the conclusion that the LSP is a mainly higgsino neutralino of mass about 50 GeV.

Of course, if superpartners are indeed being detected, it is very important for the development of particle physics and astrophysics and cosmology. It is also very important for more mundane, practical reasons – all of the planning and studies and panels for future utilization and development and construction of experimental facilities for particle physics is effectively based on the assumption that no major discoveries will be made at LEP or FNAL. If Higgs bosons and/or superpartners are found at LEP or FNAL, then those facilities will be able to study them if resources are put into luminosity and detectors and perhaps small marginal energy increases at LEP. Much more energetic facilities may also be of value, but how valuable they are depends on what is found.

\( R_b, BR(b \to s\gamma), \) and \( \alpha_s \)

As Fig. 2 illustrates, in a supersymmetric theory the two processes \( R_b \) and \( b \to s\gamma \) are related because the same superpartners occur in loops. In particular, as described in the introduction, if supersymmetry is not too broken, as is the case for the models of figure 1, then \( BR(b \to s\gamma) \) will be smaller than its Standard Model value. In that case, as shown in figure 3, \( R_b \) must be somewhat larger than its Standard Model value for these models. (The calculations used to determine the enclosed region in figure 3 are based on work in progress with M. Carena, C. Wagner, G. Kribs, and S. Ambrosanio.) Although neither \( R_b \) nor \( b \to s\gamma \) gives a significant deviation for the Standard Model, the combined effect is more significant. Figure 3 shows both the world average and the past year’s data for \( R_b \).
Further, there is a constraint that must be satisfied. If $R_b$ is in fact increased by the chargino-stop loop, but if that effect is not taken into account when $\alpha_s(Z)$ is deduced from LEP data, then the resulting $\alpha_s(Z)$ from $\Gamma_Z$ will be somewhat larger than the true $\alpha_s$. Quantitatively, $\delta \alpha_s^\Gamma \approx 4 \delta R_B$. If $\delta R_B \approx 0.0012$, say, then $\delta \alpha_s \approx 0.005$. Presently, $\alpha_s^\Gamma = 0.121 \pm 0.003$, while the world average without the $\Gamma_Z$ value is $0.117 \pm 0.003$, so a shift of 0.005 is very consistent. If this had failed the whole picture would have been wrong (e.g. if the world average was above $\alpha_s^\Gamma$). I don’t know how to assign a quantitative measure to the comparison of SUSY and the Standard Model here, but the combined effect of the three observables is certainly of some interest.

The CDF $e^+e^-$ Event

The reported CDF event is interesting for four reasons. (1) Most important, the probability of the Standard Model giving such an event is, as far as is known, extremely small, less than $10^{-4}$ from naive use of the theory and probably considerably smaller when experimental considerations are included. While one event can never be a convincing signal, it is important to understand that this event is interesting because it should not have occurred in the Standard Model. (2) The event has $\sim 50$
GeV $E_T$, as expected for SUSY events. (3) It also has hard isolated $\gamma$’s, predicted long ago as one likely way to detect superpartners. (4) A number of conditions, cross sections, branching ratios etc. have to come out right or such an event could not qualify as a SUSY candidate. It is not easy to satisfy the conditions. Here I want to emphasize that one way to get the photons, and to interpret this event as production and decay of superpartners, is for the LSP to be mainly higgsino, and for the next-to-LSP to be mainly photino. That interpretation implies the parameters of figure 1, in a way completely independent of the $R_b, b \rightarrow s\gamma, \alpha_s$ data. It only uses general features of the CDF event, the presence of energetic isolated $\gamma$’s and $E_T$.

**Electroweak Baryogenesis**

Increasingly detailed calculations have been done to determine if the baryon asymmetry of the universe can be generated at the electroweak scale during the electroweak phase transition. Recent work has concluded that the answer is quantitatively “yes” if charginos and stops have masses of order the EW scale, and in particular if $\tan \beta$ is near $1$, $|\mu| < M_1 \sim M_2$, $M_h \lesssim 80$ GeV, and there is a light, mainly right-handed stop. These are just the same parameters arrived at by the other phenomena we consider, and shown in figure 1.

**LEP $\gamma\gamma E$ Events**

Combining LEP data from 161 and 172 GeV, and four detectors, about six events have been reported for $e^+e^- \rightarrow \gamma\gamma+$ nothing, with missing invariant mass $M$ in the region above $M_Z + 10$ GeV. We can view the occurrence of such events as a prediction of the higgsino – LSP picture suggested by the presence of the photons in the CDF event, or equivalently as a prediction of the $R_b + b \rightarrow s\gamma + \alpha_s$ data. In either case the events come as $e^+e^- \rightarrow \tilde{N}_2(\rightarrow \gamma\tilde{N}_1)\tilde{N}_3(\rightarrow \gamma\tilde{N}_1)$. There is background for such events from $e^+e^- \rightarrow \nu\bar{\nu}$ with two radiated $\gamma$’s. Assuming $M_{\tilde{N}_2} - M_{\tilde{N}_1} > 20$ GeV to ensure that energetic photons are likely at FNAL, the signal has $E_\gamma \gtrsim 8$ GeV while the background peaks at $E_\gamma \rightarrow 0$. If $M_{\tilde{N}_2} - M_{\tilde{N}_1}$ is allowed to decrease to (say) 15 GeV, the minimum $E_\gamma$ decreases to about 5 GeV. By making a cut $E_\gamma \gtrsim 8$ GeV the background cross section is about 1.3 events in the region above $M_Z + 10$, where the entire signal should occur since $M > 2M_{\tilde{N}_1} \cong 100$ GeV. If we turned the analysis around and asked what would be required if about 6 such events with 1.3 expected constituted a signal, we would find again $\tan \beta$ near 1, $|\mu| < M_1 \sim M_2 \sim M_Z$, as shown in figure 1. For LEP184 with $\gtrsim 50$pb$^{-1}$ per detector, the $E_\gamma$ cut can be increased to reduce background relative to signal.

**Gluinos and Squarks at the Tevatron?**

It has been argued that an interpretation of the Fermilab data based on the assumptions that $M_{\tilde{g}} \gtrsim M_t + M_\tilde{t}$ and $M_{\tilde{q}} \gtrsim M_{\tilde{g}}$, with $\tilde{g}$ and $\tilde{q}$ otherwise as light as possible, is at least as consistent as the Standard Model interpretation and perhaps
more so in describing reported top-quark data from Fermilab. Some tops arise from \( \tilde{g} \to t + \tilde{t} \), the dominant gluino decay since it is the only 2-body one, and some tops decay into stops, \( t \to \tilde{t} + \tilde{N}_{1,2} \). If a light stop exists such an extra source of production of tops may be needed for a consistent set of top production and decay data. The total cross section for \( \tilde{g} + \tilde{q} \) production (\( \tilde{g} \tilde{g}, \tilde{g} \tilde{q}, \tilde{q} \tilde{q} \)) is about 5 pb, about the same as the Standard Model \( t\bar{t} \) cross section for 175 GeV top. Cross sections for different topologies ( dilepton events, \( W + \) jets events, and six jet events) will be affected differently and will give different values. The total top cross section will exceed the Standard Model one unless very tight cuts are imposed. Some features of the events, such as the \( P_T \) of the \( t\bar{t} \) pair, will behave differently. All of these phenomena are at least as consistent with the SUSY predictions as with the SM. If this is happening it requires a stop and an \( N_1 \) that are not very heavy, consistent with the values in figure 1.

## Cold Dark Matter

The LSP resulting from the above analyses has well determined properties. It is a candidate for the cold dark matter of the universe. If the CDF event or the LEP \( \gamma\gamma \bar{E} \) events actually are evidence of superpartners, then the LSP has effectively been observed in the laboratory. It is mainly a higgsino, approximately the superpartner of the Higgs boson. Before we can conclude it is providing much of the cold dark matter, we must calculate its relic density. It could overclose the universe, in which case the whole picture presented here would be wrong, or it could provide a negligible amount of CDM because it annihilates too efficiently. In fact, for the parameters of figure 1 (it depends on \( \tan \beta, \mu, M_1, M_2 \)) calculations give \([14]\) a relic density just about right to provide a flat universe with \( \sim 2/3 \) CDM (\( \Omega_{CDM}h^2 \sim 1/4 \) to a factor of two or so). We could again turn it around, insist that the parameters be such as to make the LSP a good CDM candidate quantitatively (since supersymmetry provides such a candidate, which has been known for almost two decades, surely we do not want to give up that opportunity). Then the solution is not unique, but if we insist on a CDM candidate and also that any of the CDF event, or LEP events, or \( R_b + b \rightarrow s\gamma + \alpha_s \), or electroweak baryogenesis are real effects of supersymmetry then the solution is uniquely the parameters of figure 1.

## Light Higgs Boson

In a supersymmetric world the mass of the lightest Higgs boson can be at most about 150 GeV. Present analyses give \( m_{h^0} = 117 \pm 10^{7.6} \) or \( m_{h^0} < 375 \) GeV at 95% CL from the LEP working group,\([5]\) and \( m_{h^0} = 101.0 \pm 99.7 \) or \( m_{h^0} < 312 \) GeV at 95% CL from the analysis\([13]\) of Degrassi, Gambino, and Sirlin, which includes \( \alpha^2 m_t^2 \) contributions that are not yet in the LEP working group treatment. Thus there is finally statistically significant evidence for a light Higgs boson, a necessary condition for SUSY to hold. At this level of numerical evidence there are no implications for SUSY parameters. However, the tree-level \( m_h \) has an upper limit of \( M_Z|\cos 2\beta| \) and
that is suppressed with $\tan \beta$ near one. Also, the top loop radiative correction to $m_h$ is suppressed with a light $\tilde{t}_R$. Thus the parameters of figure 1 imply a relatively light $m_h$, in the range below about $M_Z$ and more likely in the smaller part of the range. That $h^0$ couples rather like a Standard Model $h$, and is likely to be observed at LEP2. It will certainly be observed at FNAL if it is a little heavy for LEP2.

**Consistency With Other Data, and LEP184 Predictions**

With the parameters in the figure 1 range we can ask what other experimental predictions can provide tests. As soon as the masses of neutralinos and charginos are in the kinematical range allowed by LEP the production cross sections for some channels become large. In particular, $e^+e^- \rightarrow \tilde{N}_1\tilde{N}_3$ is at the pb level, so dozens of events must have already been produced at LEP if figure 1 is correct. They were not observed. Does that already exclude this picture?

A little analysis shows that one simple mass ordering immediately implies that almost all $\tilde{N}_3$ decays are invisible. So long as $M_{\tilde{N}_3} > M_{\tilde{C}_1} > M_{\tilde{\nu}} > M_{\tilde{N}_1}$ then all data at LEP and FNAL is consistent with the results of Figure 1. This is the unique way to have $\gamma\gamma E$ events without many $\tilde{N}_1\tilde{N}_3$ events.

For this mass ordering, $\tilde{\nu} \rightarrow \nu \tilde{N}_1$ dominantly (with a small BR for $\tilde{\nu} \rightarrow \nu \tilde{N}_2(\rightarrow \gamma \tilde{N}_1)$); $\tilde{\nu}$ is mainly invisible. So $e^+e^- \rightarrow \tilde{\nu}\tilde{\nu}$ is a large cross section but mainly unobservable. And $\tilde{N}_3 \rightarrow \tilde{\nu}\nu$ dominantly so if $\tilde{\nu}$ is invisible so is $\tilde{N}_3$. Thus not only the LSP, but also $\tilde{\nu}$ and $\tilde{N}_3$ are effectively invisible.

From these channels, particularly from $\tilde{N}_2(\rightarrow \gamma \tilde{N}_1)\tilde{N}_3$, and from radiation of a detected initial $\gamma$, a detectable excess is predicted to occur for $e^+e^- \rightarrow \gamma + \text{invisible}$, with the excess having a minimum recoil mass $M$ of at least $M_{N_1} + M_{\tilde{\nu}}$ for some events, and at least $2M_{\ell}$ for others, i.e. the excess is only at larger missing invariant mass well over 100 GeV. About 80% of the excess is from decays, the rest from radiated initial hard $\gamma$’s. One other visible channel will be $e^+e^- \rightarrow \tilde{N}_2(\rightarrow \gamma \tilde{N}_1)\tilde{N}_2(\rightarrow \gamma \tilde{N}_1)$, already described above.

Signatures for charginos and stops also become nonstandard; $e^+e^- \rightarrow \ell^+\ell^- M$, with large $M$ and therefore soft leptons, will dominate for charginos ($\tilde{C}^{\pm} \rightarrow \ell^+\tilde{\nu}$). Here $\ell, \ell'$ are charged leptons perhaps of different types. Detailed signatures are described in ref. 11. Since the chargino mass is not much larger than the sneutrino mass, the leptons can be very soft, perhaps only one or two GeV. There is no background from $W^+W^-$ for these soft leptons. Thus charginos should appear at LEP2 as events with, say, a one-GeV electron and a 2 GeV muon, acoplanar and acolinear, and nothing else.

**Extracting Supersymmetry Physics From Supersymmetric Data**

Even if the results described here do not turn out to correspond to reality, the analysis represents an existence proof that the combination of some data and the tightly
constrained SUSY theory is powerful enough to allow us to extract the relevant masses and SUSY Lagrangian parameters from the data with pretty good accuracy. This was aided by the presence of the photons here, but a similar situation will hold whatever the form the data takes. Here we have used a very general softly broken supersymmetric effective Lagrangian to proceed, with very few assumptions. Assumptions about soft-breaking parameters are useful to study the behavior of the theory before there is data, but once there is data the parameters should be measured and assumptions tested. Measuring the parameters of the general effective supersymmetric Lagrangian at the EW scale will be challenging, but fun and doable, particularly by combining information from different experiments.

Implications for Theory

If we are not being misled by the interesting but not individually compelling experimental hints of physics beyond the Standard Model, and by the fact that they all imply the same set of SUSY parameters — which would be remarkable if they were just fluctuations or systematic errors — then the results of figure 1 may provide significant information about the form of the effective Lagrangian at the unification scale (GUT or string unification). $\tan \beta$ may be\[7, 9\] very near or even below its perturbative lower limit, which could provide information about intermediate scale matter. $M_1$ may be about equal to $M_2$ rather than the naive prediction $M_1 = \frac{5}{3} \tan^2 \theta_W M_2 \approx \frac{1}{2} M_2$, which would provide important information about soft-breaking terms\[7,9\]. $M_{\tilde{e}_L}$ may be less than $M_{\tilde{e}_R}$, which could\[15\] come from D-terms associated with a new $U(1)$ symmetry, and help determine its charges. In the MSSM with superpartners below about a TeV it is necessary\[17\] that $\alpha_s(Z)$ be about 0.13, certainly larger than 0.125. If $\alpha_s(Z) = 0.117$ from experiment, new effects must reduce the predicted $\alpha_s$. However the results finally come out, we can be optimistic that we will be able to learn a great deal about the form of the theory near the Planck scale from data at the EW scale combined with relevant theory.

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