Sphenomenology — An Overview, with a Focus on a Higgsino LSP World, and on Eventual Tests of String Theory*

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In this talk, as requested, I begin with an overview and with some basic reminders about how evidence for supersymmetry in nature might appear – in particular, how SUSY signatures are never clear so it is difficult to search for them without major theoretical input. Models can be usefully categorized phenomenologically by naming their LSP – that is, once the LSP is approximately fixed so is the behavior of the observables, and the resulting behavior is generally very different for different LSPs. Next I compare the three main LSP-models (gravitino, bino, higgsino). Hints from data suggest taking the higgsino-LSP world very seriously, so I focus on it, and describe its successful prediction of reported events from the 1996 LEP runs. SUSY signatures in the \( \tilde{h} \) LSP world are very different from those that are usually studied. Then I briefly discuss how to measure the parameters of the effective Lagrangian from collider and decay data. Finally I turn to how data will test and help extract the implications of string theories.

1. INTRODUCTION

The traditional arguments for supersymmetry continue to be compelling. If nature is supersymmetric on the electroweak (EW) scale it provides a solution of the hierarchy problem, it allows unification of the Standard Model (SM) forces, local supersymmetry is connected to gravity, it provides a derivation of the Higgs mechanism (and in that context predicted that \( M_t \) would be large), and it provides a candidate for cold dark matter.

It is thus natural that much work has focussed on asking whether nature is indeed supersymmetric at the EW scale. Explicit experimental proof is required. Once we have that proof we have to do better, to measure the soft-breaking terms (and eventually their phases and flavor properties) and \( \tan \beta \) and \( \mu \). The values of these parameters will point toward the correct vacuum, and toward how SUSY is broken.

It would be very nice if clean, unambiguous experimental signals could appear one day. But a little thought tells us that is unlikely — probably impossible. Consider colliders. At least until the LHC, which is unlikely to produce its first paper relevant to supersymmetry until well over a decade from now, what will happen is that as energy and/or luminosity increases at LEP and FNAL a few events of superpartner production will occur. Perhaps such events have already occurred. Each event has two escaping LSP’s, so it is never possible to find a dramatic \( Z \)-like two body peak, or even a \( W \)-like peak with one escaping particle. Even worse, often several channels look alike to detectors so simple features can be obscured. And usually there are SM processes that can fake any particular signature, as well as ways to fake signatures because detectors are imperfect.

Thus to make progress it is essential to proceed with limited amounts of incomplete information. Without theory input it is entirely possible that signals would not be noticed, hidden under backgrounds since there was no guide to what cuts to use (an example is discussed below). Further, a particular signal might be encouraging but not convincing – only when combined with other signals that were related by the theory but not directly experimentally could a strong case be made.

What about information from decays? In the

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best cases, such as \( b \to s \gamma \), where there is no tree level decay, the SUSY contribution could be comparable to the SM one, say a large effect of order 30\%. Then to get a significant effect the combined errors of the theoretical calculation of the SM value and the experiment have to be below 10\%. Only \( b \to s \gamma \) of known decays can approach that; presently the theoretical error\([1]\) is at about that level, and the experimental error about 20\%. At best, in a couple of years this could provide compelling evidence of new physics. If so, taken alone several interpretations would be possible, but with theoretical input it could be combined with collider data to determine which were consistent.

When there is a tree level SM contribution, such as for \( R_b = \Gamma (Z \to b \bar{b}) / \Gamma (Z \to \text{hadrons}) \) the SUSY effect has to be a loop and can be \( \sim \frac{1}{2} \% \), so experimental errors have to be several times smaller. Just from statistics that requires \( \sim 10^6 \) events, which is unlikely. Sometimes several decays are related in a particular model, in which case the combined predictions can be tested and the results are somewhat more significant (that is the situation for \( b \to s \gamma \) plus \( R_b \) plus \( \alpha_s \)). Further input could come from proton decay to channels favored by SUSY, from occurrence of decays forbidden in the SM such as \( \mu \to e \gamma \) or \( K \to \mu e \), from neutron or electron electric dipole moments, from non-SM CP violation, or other rare phenomena.

If we can discover superpartners before LHC, it will be necessary to proceed with fragments of information, check their consistency, make predictions to test them, and slowly build a case. We will see below that there are things to work with (which need not have happened – most fluctuations from the SM could never be interpreted as SUSY). There is now some evidence for one prediction based on those hints. A number of predictions at LEP and FNAL can test whether this interpretation, based on the higgsino-LSP world, actually describes nature.

2. COMPARISONS

Almost all of the studies of supersymmetric models can be classified according to what is the LSP, and fall in three categories, as shown in Table 1. On the left are listed several criteria that are often used to compare and test models. The first world listed has a light gravitino LSP (GLSP), the second an LSP that is mainly bino (BLSP) and the third mainly higgsino (\( \tilde{h} \)LSP). The implications for SUSY-breaking and experimental signature are very different for the three cases – it will be easy to recognize which is being observed once one is detected. (GLSP) corresponds to gauge-mediated SUSY-breaking, and the other two gravity-mediated SUSY-breaking.) Some of the individual criteria will be described in more detail below in the (\( \tilde{h} \)LSP) section; see also ref. 2.

In a \( \tilde{G} \)LSP world there is a small window for a signal at LHC but no reason to expect one there. If the CDF event\([3]\) were interpreted as evidence for a \( \tilde{G} \)LSP world, which is difficult given constraints but not excluded, many such events would occur at FNAL after the collider starts running again in 1999; otherwise there is only a small window at FNAL. Such a world could probably be detected at LHC or a lepton collider about 2010.

In a \( \tilde{B} \)LSP world there is no evidence today for sparticles, and all hints must disappear (no more \( ee\gamma\gamma E_T \) events at FNAL; \( BR(b \to s \gamma) \) → SM, \( R_b \) → SM, \( \alpha_s^\gamma - \alpha_s^\text{other} \to 0 \); no future excess of \( \gamma\gamma E \) events at LEP; baryogenesis not at EW scale; etc.). There are small windows at LEP and FNAL but no reason for sparticles to be there. Such a world probably will be detected at LHC or a lepton collider about 2010.

In a \( \tilde{h} \)LSP world sparticles may have already been observed. Confirmation will occur at LEP\([4]\) once 50 \( \text{pb}^{-1} \)/detector at \( \sqrt{s} \gtrsim 190 \text{ GeV} \) has been accumulated or before. In the next section the hints for an \( \tilde{h} \)LSP world and some of the tests are described in a little more detail.

3. \( \tilde{h} \)LSP WORLD

Here we will need some notation. \( \tilde{N}_i \) are the four neutralino mass eigenstates, \( \tilde{C}_i \) the two chargino ones, and \( \tilde{t}_1 \) the lighter stop mass eigenstate. \( M_1 \) and \( M_2 \) are the \( U(1) \) and \( SU(2) \) soft-breaking gaugino masses, \( \mu \) the coefficient of
| Evidence/Criteria                        | $\tilde{G}LSP$ | $\tilde{B}LSP$ | $\tilde{h}LSP$ |
|------------------------------------------|----------------|----------------|--------------|
| Absence of FCNC                          | Yes, if messenger scale low | Mechanisms exist, but don’t know if they are applicable |
| Number of parameters                     | Presently all about same – $\tilde{G}LSP$ somewhat more than others now, but will be more predictive after squarks and sleptons observed. |
| CDF $e \, “e” \, \gamma \gamma \not{E}_T$ | maybe | no | yes |
| $R_b, BR(b \to s\gamma), \alpha_s$       | maybe $bs\gamma$ | no for $R_b, \alpha_s$ | no | yes |
| LEP $\gamma \gamma \not{E}$ events      | no | no | yes |
| Cold Dark Matter                         | not LSP | ok | yes |
| $\tilde{g}$, light $\tilde{t}$ at FNAL? | no | no | ok |
| EW baryogenesis                          | no | no | ok |
| $m_{h^0} \lesssim M_Z$                   | no reason | no reason | yes |
| typical signatures that distinguish      | (a) either 2 $\gamma$’s in every event; or 2 charged leptons in every event; or long-lived particles that decay in or outside of detector (b) medium $M$ | (a) no $\gamma$’s; (b) events with no charged leptons; (c) larger $M$ (d) trilepton + $\not{E}$ events at FNAL, LHC | (a) 0, 1, or 2 $\gamma$’s (b) large $M$ (c) not only LSP but also $\nu, N_3$ invisible |
$H_U H_D$ in the superpotential, and $\tan \beta$ the ratio $< H_U > / < H_D >$.

All the phenomenological analysis can be done with a general soft-breaking effective Lagrangian written at the electroweak scale. One can fully analyze the CDF event, the LEP $\gamma \gamma E$ events, $b \to s \gamma$, $R_0, \alpha_s$, EW baryogenesis and cold dark matter with only 5 major parameters ($\mu, \tan \beta, M_1, M_2, M_{1\tilde{t}}$). The complete detailed analysis also depends on the stop section mixing angle, and the sneutrino and $\tilde{\epsilon}_R$ masses but not sensitively. The other parameters of the Lagrangian will enter once more sparticles are being detected.

I don’t have space here to give details about most of the entries in the table; a recent summary is available in ref. 2. Here I will only mention the LEP $\gamma \gamma E$ events since they have had less exposure. In 1986 we argued that collider events with hard isolated photons would be a good signature for supersymmetry, coming from $\tilde{\gamma} \to \gamma \tilde{h}$. In Jan. 1996 we learned about the CDF event, and analysis showed it could indeed be interpreted as a SUSY candidate. Further analysis showed consistency (same parameters) with other hints of evidence for SUSY. Consequently, we predicted that several confirming channels could show up at LEP or FNAL.

One of the confirming channels is events with two hard $\gamma$’s at LEP, from $e^+ e^- \to N_2 \bar{N}_2$ followed by $N_2 \to \gamma N_1$. $N_2$ is mostly $\tilde{\gamma}$ and $N_1$ mostly $\tilde{h}$. Such events must have missing invariant mass $M$ above $2 M_{LSP} \sim M_Z$; since there is a large background with $M \simeq M_Z$ one should make a cut with $M \gtrsim 100$ GeV, which loses little or no signal. Given the motivation from other data there should be a minimum $E_\gamma \gtrsim 5$ GeV so a cut at (say) 5 GeV for both photons gets rid of most of the soft $\gamma$ background. The signal is isotropic while the background peaks sharply near the beam so a cut of (say) $|\cos \theta| < 0.85$ gets rid of a large background at a relatively small loss in signal.

About 6 candidates have been reported for $161 + 172$ GeV, 4 detectors. The “about” is needed since the full parameters of the events have not been reported. With these cuts the background cross section is about 0.025 pb, so at 161 + 172 GeV for 4 detectors the background is about 1.5 events for detection efficiency of 3/4. This number assumes an increase of about 35% over the tree level for radiation of extra undetected $\gamma$’s. No general background calculations have been completed so these numbers are estimates based on the information in ref. 11.

While not yet compelling, such a result is certainly encouraging. Mahlon and I have catalogued several tests that will be carried out at LEP as soon as it gets near its design luminosity at higher energies.

In the absence of one very convincing channel, we have to look at the pattern of several processes as I explained in the introduction. This is in a good tradition – in the 1970’s checking that $\sin^2 \theta_W$ was consistent with a single value when measured different ways was one of the main ways we gained confidence in the EW theory. Much earlier, checking that Avagadro’s number had the same value when measured many different ways was considered the strongest argument for the physical existence of atoms near the beginning of this century.

Each of the experimental hints I mentioned is about as strong as it could be given existing integrated luminosities and experimental errors. Each can only be interpreted as evidence for SUSY if the parameters ($\mu, \tan \beta, M_1, M_2, M_{1\tilde{t}}$) take on a small range of values. If we were being misled by the data, if these phenomena were not evidence for SUSY, it is very unlikely that all would have given consistent quantitative descriptions for the same parameters. Very encouraging. Conservatively, finding the same parameters is a necessary condition, but of course not sufficient.

Signatures at LEP and FNAL are interesting and rather different from the usual ones. $\tilde{\nu}$ is light, and dominantly decays $\tilde{\nu} \to \nu \tilde{N}_1$ so it is mainly invisible. $N_2 \to \gamma \tilde{N}_1$ as discussed above, giving $\gamma \gamma E$ events from $e^+ e^- \to N_2 \bar{N}_2$. $N_3 \to \nu \tilde{\nu}$ dominates so $N_3$ is mainly invisible. $\tilde{C}_1^\pm \to \ell^\pm \tilde{\nu}$ dominates, and $m_{\tilde{C}_1} - m_{4\ell}$ is small so the leptons can be very soft. Production of $N_2 \bar{N}_3$ gives events with one $\gamma$ and large missing energy, and several other channels also contribute to this signature.
All of these channels can be seen at LEP but could be missed if appropriate cuts and analyses were not made. In particular, for $\gamma\gamma\not{E}_T$ events if photons softer than $\sim 5$ GeV are included the background will increase rapidly and a signal could be hidden.

4. FROM DATA TO $\mathcal{L}_{\text{EFF}}$

Actual measurements of effects of superpartners will produce cross sections and distributions, excesses of events with some set of particles such as gammas and perhaps with missing energy. They do not produce measurements of the masses or couplings of superpartners, and determination of the soft-breaking parameters or $\mu$ or $\tan\beta$ is even less likely. Most distributions get contributions from several processes as well. How can we proceed to extract the physics parameters of interest from data in such a nonlinear situation?

Some analyses already exist\[13\], mainly for $e^+e^-$ colliders (where results are often simpler) rather than hadron colliders, and for a few idealized cases. These already show that useful general results can be obtained in such situations.

In fact, the general problem has been addressed and a procedure given\[14\] to extract the sparticle masses and/or the parameters of $\mathcal{L}_{\text{EFF}}$. Every measurement provides information. There is an excess of events at a certain cross section level in one process, none in another. The optimum procedure is to randomly select values for all parameters, calculate all observables, and discard values of parameters that give observables in disagreement with data. In practice I expect it to be the other way, as it has been throughout the history of physics – once we know the vacuum is known the latter will be determined, and also how SUSY was broken (perhaps once the vacuum is known the latter will be determined), then the $\mathcal{L}_{\text{EFF}}$ could be predicted, and compared with the $\mathcal{L}_{\text{EFF}}$ deduced from data. In practice string theory, on the other hand, starts somewhat above the unification scale, at the Planck scale. If the way to select the vacuum was known, and also how SUSY was broken (perhaps once the vacuum is known the latter will be determined), then the $\mathcal{L}_{\text{EFF}}$ could be predicted, and compared with the $\mathcal{L}_{\text{EFF}}$ deduced from data. In practice string theory provides strong constraints so the actual number needed can be smaller than $N$. Also, often it is easy to put limits on parameters that reduce the size of the problem after a little thought. This method could already be used to get general limits on sparticle masses, but so far only parameter dependent limits have been published as far as I know. This procedure has been used in references 4, 6.

5. MEETING AT THE UNIFICATION SCALE

As data about superpartners is increasingly available, more and more of the parameters of the effective Lagrangians $\mathcal{L}_{\text{EFF}}$ of the theory at the electroweak scale will be measured. Constraints from rare decays, CP violation, baryogenesis etc. will be included. Then, assuming the theory to be perturbative to the scale where the gauge coupling unify, the effective Lagrangian at that scale will be calculated by using renormalization group equations.\[15\] It is not necessary (nor expected) that there be a desert in between, but only that the theory be perturbative. Intermediate matter and scales are expected. There will be consistency checks that allow the perturbativity to be confirmed. Since constraints occur at both ends it is not just an extrapolation. Unification may or may not involve a unified gauge group.

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In the hLSP world some interesting preliminary results have been obtained (by the method of the previous section). Whether these results persist as better data is obtained or not, they encourage one to think we will be able to learn about unification scale physics from EW scale data. Some examples:

(a) The usual “unification” assumption for gaugino masses has $M_1 = M_2$ at the unification scale. Then the RGE running gives $M_1(M_2) = \frac{5}{3} \tan^2 \theta_W M_2(M_2) \approx \frac{1}{2} M_2(M_2)$. If the CDF event and/or the LEP $\gamma\gamma\not{E}_T$ events are indeed pro-
duction of superpartners in a higgsino LSP world, then we know $BR(N_2 \rightarrow N_1 \gamma)$ is large. Examination of the neutralino mass matrix\cite{16} shows that this $BR$ is maximal when $M_1(M_Z) \cong M_2(M_Z)$, and for it to be $\gtrsim \frac{1}{2} M_2(M_Z)$. This in turn implies that the simple unification condition does not hold, which means we are learning about unification scale physics from collider data. A similar result for $M_1(M_Z)/M_2(M_Z)$ has been found in ref. 16.

Note that it will be interesting to understand how to interpret this result. It could directly point toward a theory where $M_1(M_U) > M_2(M_U)$. Or it could, say, imply that the true neutralino mass matrix is of the form

$$
\begin{pmatrix}
M' & M_1 \\
M_1 & M_2 \\
\vdots
\end{pmatrix}
$$

because of an extra $U(1)$. Then the trace of this is $M'_1 + M_1 + M_2 + \ldots$ so if we have an effective $4 \times 4$ neutralino mass matrix what we call $M_1$ is really $M_1 + M'_1 > M_1$.

(b) Most of this phenomenology suggests $\tan \beta$ is near or below its naive perturbative lower limit. But that is subtle. It depends sensitively on $M_{\text{top}}$ (if $M_{\text{top}}$ decreases from 175 GeV to 163, the naive lower limit on $\tan \beta$ decreases from 1.76 to 1.38), and the value of $M_{\text{top}}$ should not be taken as settled yet. SUSY-QCD effects\cite{15} lower the limit below the naive one. Also, new physics at intermediate scales could affect this lower limit which would be very interesting.

(c) In the MSSM, if $\alpha_s(M_Z) \lesssim 0.125$ then sparticles must be heavier than about 1 TeV if the three gauge couplings exactly unify.\cite{19} But the world average is $\alpha_s = 0.117 \pm 0.003$ (for consistency this should be calculated leaving out the $\alpha_s$ from $\Gamma_Z$). So if there is any evidence for sparticles then some additional physics must affect the running of the gauge couplings. A number of possibilities exist and it will be very interesting to elucidate which one(s) occur.

(d) If a new $U'_1$ symmetry exists, with a $Z'$ at the TeV scale, the $Z'$ may be too heavy and too weakly coupled to quarks and leptons (much of its coupling may be to sparticles and heavy Higgs bosons) to detect directly. But it affects squark and slepton masses\cite{20} through $D'$-terms, and through them one can determine the $U'_1$ charges. If all the details of the CDF event and LEP data were not misleading us then probably $\tilde{e}_R$ is heavier than $\tilde{e}_L$, which suggests a non-minimal contribution to the slepton masses that could come from $D'$-terms.

6. TESTING STRING THEORY

A myth has grown that string theories are not normal testable physics. The myth began in the middle 1980’s, partly as a reaction to excessive enthusiasm from proponents of string theory. We have learned a lot since then.

The myth is wrong. String theory is testable normal science. You don’t have to go somewhere in space or time to test a theory about there. We know many examples. The big bang theory is well tested by its correct predictions now of the expansion of the universe, nucleosynthesis, and the cosmic microwave background radiation even though we can’t go back to observe it. The composition of distant stars, the facts that they are made of the same atoms as our star and us, and that they obey the same rules of quantum theory and relativity as hold in our part of the universe, can be learned by understanding spectra and redshifts and making appropriate observations without going there. We can learn how the dinosaurs became extinct without watching them die.

It is always crucial to go through chains of reasoning and to do complicated calculations in order to perform the tests. That is true of all the above examples, and equally true of physics today. Condensed matter physicists believe they have a quantitative understanding of phase transitions. That belief is based on complicated renormalization group analyses, involving exactly the same techniques used to connect physics at the electroweak scale to physics at the Planck scale—it is even true in both cases that at the place one wants most to study the theory is expected to become non-perturbative. Parity violation in atoms is thought to be a quantitative test of the SM even
though very complicated calculations are needed to go from observing an effect to extracting the couplings of the Z to quarks and leptons. Calculations will also be needed in the string case but that does not mean it is less testable than other normal physics.

String theory is not yet very tested or predictive. The techniques to change that are being learned. As always in physics, one proceeds by making assumptions and calculating, and slowly improving the results. Normally it takes a while to get it right.

In the following I give some examples to make concrete how many tests there will eventually be of string theory. As is well understood, it is necessary to have not only the theory, but also to know the vacuum. Presumably determining the correct vacuum also determines how supersymmetry is broken and vice versa, but in practice there might be progress in one or the other of these first. As I said earlier, I expect data will be necessary to make progress on these.

It is useful to give examples in six categories. Note that no super-high energy facilities are needed for any of the examples. I list a number of examples; more will exist. In order to not give dozens of references here I will give none, with apologies to the many people who have discussed these ideas and observables.

(a) Profound questions. If a theory can provide a definition of space-time, or derive the existence of three and only three non-compact space dimensions, or explain what a particle is, or explain what electric charge is, or explain the value of the cosmological constant, or solve the black hole information loss puzzle, that theory has passed a major test.

(b) Why questions. Why are there three chiral families of quarks and leptons? Why is general relativity the correct theory describing gravity (or whatever is)? Why is nature supersymmetric? Why is the SM gauge group $SU(3) \times SU(2) \times U(1)$? Why is matter quarks and leptons but not leptoquarks?

Every answer to a “profound question” or “why question” is a powerful test of a theory. Many of these questions are true stringy ones rather than ones likely to hold in any high scale theory.

(c) Very low energy phenomena – no collider needed. String theories provide expressions for fermion masses, though so far they cannot be evaluated. Eventually there will be a calculation of (say) $m_\mu/m_\tau$ (a useful ratio because it is not too sensitive to small corrections). Once the quark mass matrix can be written in the $SU(2) \times U(1)$ basis it can be diagonalized and the CKM angles, including the weak phase, calculated. A string theory will predict whether the proton decays, and if so its lifetime and branching ratios; the decay may be forbidden by symmetries even if the theory has a unified gauge group. Neutrino masses and mixing angles come from physics beyond the SM and should be predicted. The strong CP problem should be explained by a string theory. Forbidden decays such as $\mu \to e\gamma$ and $K \to \mu\nu$ may be induced and their rates predicted. The phases of the soft-breaking terms may be learned from the electric dipole moments of the neutron and electron, and from $\epsilon_K, \epsilon_B$, and $B_d, B_s$ mixing. The baryon asymmetry of the universe provides information on magnitudes and phases of soft-breaking masses and $\mu$ and $\tan \beta$. Possibly laboratory cold dark matter experiments will measure the mass and couplings of the LSP.

(d) Collider phenomena. Once superpartners are being studied we will have over 30 of their masses to test any theory of SUSY-breaking. In addition there will be a number of SCKM angles and phases, though perhaps it will be a long time before all of them can be measured. Branching ratios and missing energy events will tell us that $R$-parity and perhaps other discrete symmetries are conserved (or not). The gauge couplings and the scale at which they unify are sensitive to any predicted intermediate scale matter and to non-renormalizable operators with inverse powers of $M_{Pl}$. Extra $U_1$’s could show up as $Z'$s (which may be hard to detect, see above) or as $D'$-terms affecting squark and slepton masses.

(e) Cosmology. The scalar potential that contains the inflaton(s) and drives inflation(s) is the supersymmetric scalar potential, containing a number of scalar fields with and without SM quantum numbers. It has flat directions lifted by soft-breaking terms and Planck scale operators. The parameters in that potential not only
determine the course of inflation, they also affect or determine $\nu$ masses, the baryon asymmetry, structure formation, collider physics, gravitational waves from before the big bang, axions, etc. The dark matter from a supersymmetric unified theory is expected to contain cold dark matter determined by the LSP, and possibly cold dark matter from axions arising from breaking global symmetries of the theory, hot dark matter from neutrino masses, and baryons. The amounts and ratios of these should eventually be calculable.

(f) Unexpected. In the past all major theoretical progress has led to unanticipated predictions that were major tests, and that is likely here too. Examples are the prediction of antiparticles from unifying special relativity and quantum theory, and electromagnetic waves from unifying electricity and magnetism. Obviously I cannot say what will arise here. Perhaps there will be long range forces, or the vacuum will not respect Lorentz invariance of CPT – such phenomena have been suggested.

7. SUMMARY

- It may be hard to recognize signatures of supersymmetry at colliders without theoretical input. The standard ones used in studies are all for $\tilde{B}$LSP. The main signatures can be very different for $\tilde{G}$LSP and $\tilde{h}$LSP.

- We understand how to extract the basic soft-breaking parameters of the Lagrangian from data containing effects of superpartners, but theory is essential – there are no theory-independent signals.

- Maybe superpartners are already being observed in several ways. If so, we live in a $\tilde{h}$LSP world. If so, LEP and FNAL are the main facilities for particle physics of the 21st century – higher luminosity and better detectors are the main need for FNAL.

- To find out, watch at LEP2 for events with large missing invariant mass ($\gtrsim 100$GeV) with signatures $\gamma \gamma E, \gamma E, E^{\pm} E^{\mp} E, \ldots$.

- In a $\tilde{h}$LSP world we expect $h^0$ to be observed at LEP, and it certainly can be observed at FNAL.

- Electroweak scale data on superpartners will constrain the effective Lagrangian at the unification (GUT or string) scale and operators $\sim M_{\text{unif}}/M_{\text{Pl}}$, leading to insights about SUSY breaking and the vacuum structure.

- String theory is testable, normal science.

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REFERENCES

1. K. Chetyrkin, M. Misiak, and M. Münz, hep-ph/9612131; B. C. Greub and T. Hurth, hep-ph/9703349; Z. Ligeti, L. Randall, and M. Wise, hep-ph/9702322. See also S. Pokorski, Rapporteur’s talk at the 1996 International Conference on High Energy Physics, Warsaw, Aug. 1996.

2. G.L. Kane, Tests and Implications of Increasing Evidence for Superpartners, Talk at XXXI Rencontres de Moriond, hep-ph/9705382.

3. S. Park, “Search for New Phenomena in CDF” 10th Topical Workshop on Proton-Antiproton Collider Physics, edited by R. Raja and J. Yoh, AIP Press, 1996.

4. G.L. Kane and G. Mahlon, hep-ph/9704450, to appear in Phys. Lett.

5. H. Haber, G.L. Kane, and M. Quiros, Phys. Lett. 160B (1985) 297; H. Komatsu and J. Kühn, Phys. Lett. 157B (1985) 90.

6. S. Ambrosanio, G.L. Kane, G.D. Kribs, S.P. Martin, and S. Mrenna, Phys. Rev. Lett. 76 (1996) 3498; Phys. Rev. D54 (1996) 5395.

7. G.L. Kane and J. Wells, Phys. Rev. Lett. 76 (1996) 869.

8. J. Wells and G.L. Kane, Phys. Rev. Lett. 76 (1996) 4458.
9. G.L. Kane and S. Mrenna, Phys. Rev. Lett. 77 (1996) 3502.
10. See the talk of G. Wilson, XXXI Rencontres de Moriond, Les Arcs, France, March 1997.
11. See S. Ambrosanio, http://feynman.physics.lsa.umich.edu/ambros/Phys/2Photon+Emiss/: see also S. Mrenna, “Estimating Two Photon + Missing Energy Backgrounds to SUSY Signals at LEPII”, in preparation.
12. J. Perrin, “Atoms” 1990 reprint by Oxbow Press, Sec. 120.
13. See, for example, J.L. Geng, H. Murayama, M.E. Peskin, and X. Tata, Phys. Rev. D52 (1995) 1418; M.M. Nojiri, K. Fujii, and T. Tsukamoto, Phys. Rev. D54 (1996) 6756; M. Peskin, Prog. Theor. Phys. Suppl. 123:507 (1996); see the talk of J. Bagger at this meeting for a summary of the Snowmass 1996 studies.
14. G.L. Kane, G. Kribs, S. Mrenna, and J. Wells, Phys. Rev. D53 (1996) 116.
15. For a recent study see M. Carena, P. Chankowski, M. Olechowski, S. Pokorski, and C.E.M. Wagner, Nucl. Phys. B491 (1997) 103.
16. Ref. 6. See also S. Ambrosanio and B. Mele, Phys. Rev. D54 (1997) 1395 and references therein.
17. M. Carena, M. Quiros, A. Riotto, I. Vilja, C.E.M. Wagner, hep-ph/9702409.
18. See N. Polonsky, Phys. Rev. D54 (1996) 4537.
19. See the review of D. Pierce, hep-ph/9701344.
20. See C. Kolda and S.P. Martin, Phys. Rev. D53 (1996) 3871 and references to earlier work there; J. Lykken, hep-ph/9610218; T. Gherghetta, T. Kaeding, and G.L. Kane, hep-ph/9701343.