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Physics Goals of the Linear Collider

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ABSTRACT

I review the most important objectives of the physics program of a next-generation e^+e^- linear collider.

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PHYSICS GOALS OF THE LINEAR COLLIDER

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1 Introduction

For more than twenty years, high-energy physicists have dreamed about using linear e^+e^- colliders to extend the reach of e^+e^- annihilation to the TeV energy scale.[1] About ten years ago, with the first results from the precision electroweak experimental program at SLC, LEP, and the Tevtron, it became possible to envision a sharply focused physics program for linear collider experiments that would begin at center-of-mass energies of 400–500 GeV.[2,3] The experimental results of the past few years—in particular, the dramatic confirmation of the theory of the electroweak interactions to part-per-mil precision—have made the experiments proposed for the linear collider seem even more urgent and central to the goals of high-energy physics.

In this article, I will briefly review the most important physics objectives of the program planned for the next-generation e^+e^- linear collider (LC). Recently, a number of detailed reviews have appeared which discuss the broad array of measurements that can be performed at the LC.[4,5,6] My goal here is to highlight those measurements that, in my opinion, form the key justifications for the LC program.

Why do we expect to find new physics at the LC? The most important experimental discovery of the past decade has been the success of the Glashow-Weinberg-Salam theory of unified weak and electromagnetic interactions. This model is based on the idea that the weak and electromagnetic interactions are mediated by vector bosons associated with a symmetry group $SU(2) \times U(1)$, which is spontaneously broken to $U(1)$, the gauge symmetry of Maxwell's equations. The characteristic prediction of gauge theory is that coupling constants should be universal, and, indeed, experiments at the Z^0 have shown that that the weak and electromagnetic couplings of all species of quarks and leptons are given by two universal couplings g and g' (or e and $\sin^2\theta_w$). At the 1% level of accuracy, there are deviations from this prediction, but these are accounted for by the radiative corrections of the electroweak theory when one uses the observed mass of the top quark.[7]

This success brings into relief the fact that the foundation of the electroweak theory is shrouded in mystery. We have no direct experimental information on what agent causes the spontaneous breaking of $SU(2) \times U(1)$ symmetry, and even the indirect indications are fairly meager. In the minimal model, this symmetry breaking is due to a single Higgs boson, but the true story is probably more complex. On the other hand, the information must be close at hand. In the electroweak theory, the formula for the W boson mass is $m_W = gv/2$, and from the known value of g we can find the mass scale of electroweak symmetry breaking: $v = 246$ GeV. Simple arguments from unitarity tell us that the Higgs boson or some other particle from the symmetry breaking sector must appear at energies below 1.3 TeV.[8] But, further, models in which the Higgs boson is very heavy give electroweak radiative corrections which are inconsistent with the precision experiments. The analysis of radiative corrections requires either that the Higgs boson lie at a mass below 250 GeV, or that other new particles with masses at about 100 GeV be present to cancel the effects of a heavy Higgs boson.[7]

Unless Nature is very subtle, the first signs of the electroweak symmetry breaking sector will be found before the LC begins operation. There is a significant window for the discovery of the Higgs boson at LEP 2 or at the Tevatron. In almost every scenario, the Higgs boson or other signals of new physics will appear at the LHC. Our problem, though, is not just to obtain some clues but to solve the mystery. For this, the unique precision and clarity of information from the LC will play a crucial role.

Because the role of the LC will most likely be to clarify the nature of new physics discovered elsewhere, that role depends on what new particles are observed. In particular, it depends on the actual mechanism of electroweak symmetry breaking (EWSB). To justify the LC project at our current state of knowledge, one must be prepared to argue that, in any model of EWSB, the LC brings important new information that cannot be obtained from the LHC. Systematic analysis shows that this is the case. On the other hand, this line of reasoning put a spotlight on specific precision measurements and requires that the LC experiments be capable of performing them. I will point out a number of these crucial experiments in this review.

My survey of the LC program will proceed as follows: First, I will introduce the capabilities of e^+e^- annihilation experiments by discussing the search for contact interactions in $e^+e^- \to f\overline{f}$. Next, I will review experiments relevant to strong-coupling models of EWSB. Finally, I will review experiments relevant to weak-coupling models of EWSB.

2 Contact Interactions

Before I discuss detailed models of EWSB, I would like to call attention to the ability of the LC to make precise test of the structure of the electroweak interactions at very short distances. This study brings in a number of unique features that the LC can also use to study more complex reactions involving new particles. Here we see these features used in their simplest context, the study of $e^+e^- \to f\overline{f}$.

The study of e^+e^- annihilation to fermion pairs begins from the observation that the Standard Model cross section formulae are simple and depend only on electroweak quantum numbers. For example,

$$\begin{aligned}\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f_L \overline{f}_R) &= \frac{\pi\alpha^2}{2s} N_C \\ &\cdot \left| Q_f + \frac{(\frac{1}{2} - \sin^2\theta_w)(I^3_f - Q_f \sin^2\theta_w)}{\cos^2\theta_w \sin^2\theta_w} \frac{s}{s - m_Z^2} \right|^2 \cdot (1+\cos\theta)^2 \ . \qquad (1)\end{aligned}$$

In this formula, $N_C = 1$ for leptons and 3 times the QCD enhancement for quarks, I^3_f is the weak isospin of f_L, and Q_f is the electric charge. The angular distribution is characteristic of annihilation to spin-$\frac{1}{2}$ fermion pairs. For f_L production, the Z^0 contribution typically interferes with the photon constructively for an e^-_L beam and destructively for an e^-_R beam. Thus, initial-state polarization is a useful diagnostic. For annihilation to the τ and the top quark, the final state polarization can also be measured.

This simplicity of formulae such as (1) allow one to determine unambiguously the spin and Standard Model quantum numbers of any new state that is pair-produced in e^+e^- annihilation. Applied to the familiar particles, they provide a diagnostic of the electroweak exchanges that might reveal new heavy weak bosons or other types of new interactions. These tests can be applied independently to the couplings to e, μ, polarized τ, c, b, and light quarks. Figure 1 illustrates how the available set of observables can be used to study the couplings of a new Z^0 in four different models for its couplings.[9]

A 1 TeV linear collider would be sensitive, through these precision measurements, to a new Z^0 up to masses of about 4 TeV. A new Z^0 boson would also appear at the LHC, up to a similar reach in mass, as a resonance in e or μ pair production. However, little can be learned about its couplings if its mass is above about 1 TeV. For such a boson, the LC will fill in the picture of its couplings to quarks and leptons. Measurements of simple annihilation processes can also be used to test for new interactions that would signal quark and lepton compositeness; a 50 fb^{-1} event sample at 500 GeV would be sensitive to a compositeness scale Λ of 30 TeV.[10] More exotic effects are also possible.

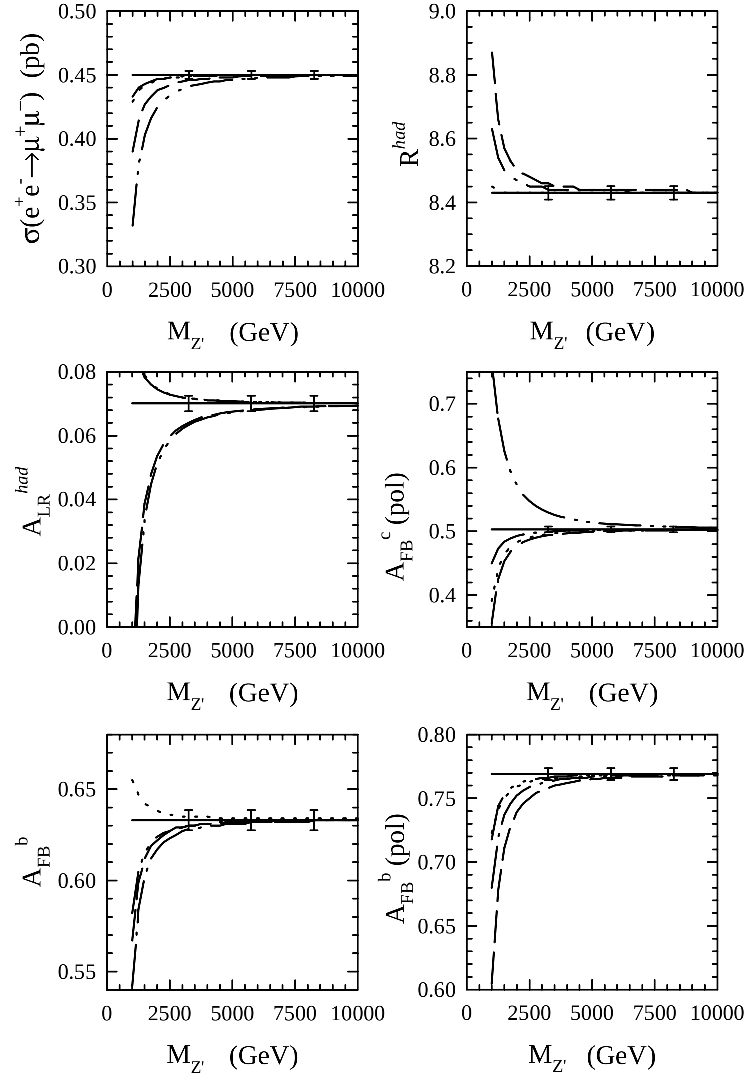

Figure 1: Deviations from Standard Model predictions for various $e^+e^- \to f\overline{f}$ processes due to a new Z^0 boson, from a study by Godfrey, ref. 9. The error bars shown correspond to a 50 fb^{-1} event sample at $E_{\mathrm{CM}} = 500$ GeV.

Recently proposed models with large extra dimensions predict contact interactions due to graviton exchange. These precision measurements can not only reveal the presence of these interactions, but also their spin-2 character.[11]

3 Strong-Coupling Route to EWSB

In the remainder of this article, I will focus on topics relevant to the question of electroweak symmetry breaking (EWSB). As I have explained above, the origin of electroweak symmetry breaking must lie in the TeV energy region. In principle, EWSB could either be generated by a weak-coupling theory with an elementary Higgs boson or by a strong-coupling theory, with the symmetry-breaking possibly due to a composite operator. Many models have been proposed that illustrate the two viewpoints. The models of the two classes have quite different phenomenological implications.

I will first consider models of EWSB due with strong-coupling dynamics. In such models, the signals of the EWSB mechanism are most clear in the properties of the heaviest Standard Model particles, the W and Z bosons and the top quark. The LC can illuminate this mechanism through its ability to study the couplings of these particles in detail. Often, the model of EWSB will also contain new particles that decay to weak bosons and third-generation fermions. The LC would allow these particles to be studied by the same techniques.

3.1 W boson

Consider first the W boson. The process $e^+e^- \to W^+W^-$ is the most important single process contributing to e^+e^- annihilation at high energy. This process also has numerous features that make it especially amenable to detailed study.

From the viewpoint of EWSB, the W is interesting because it receives mass through the Higgs mechanism. The massless W has only two degrees of freedom, corresponding to transverse polarizations. The massive W has a third degree of freedom, which corresponds to the longitudinal polarization state. This state must be stolen from the symmetry-breaking sector. In fact, it is a theorem in quantum field theory that, in the limit of high energy, the amplitude for producing a longitudinally polarized W is given precisely by the amplitude for producing the charged Goldstone boson associated with $SU(2)\times U(1)$ symmetry-breaking.[12]

Effects of new physics on the cross section for $e^+e^- \to W^+W^-$ are traditionally expressed in terms of effective 3-vector boson couplings g_{1Z}, $\kappa_{\gamma,Z}$, $\lambda_{\gamma,Z}$. These in turn are given in terms of coefficients L_i that appear in the

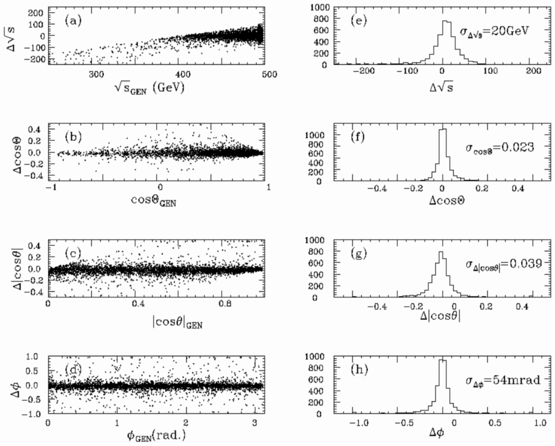

Figure 2: Reconstruction of production and decay angles in $e^+e^- \rightarrow W^+W^-$, from a simulation study by Miyamoto, ref. 15

effective Lagrangian describing the Goldstone bosons.[13] The parameter deviations predicted are rather small; for example, new strong interactions similar to QCD at TeV energies would give a deviation $(\kappa_\gamma - 1) \sim 3 \times 10^{-3}$. This should be compared with upper limits of several percent which have been obtained from LEP 2.[14]

To do better, the LC can take advantage of several features. First, the effect of the Goldstone boson couplings is naturally enhanced by a factor s/m_W^2. Second, going to higher energy separates the W^+ and W^- into opposite hemispheres and makes the kinematics more well-defined. In Figure 2, I show the results of a simulation study of events at a 500 GeV LC in which one W decays hadronically and the other leptonically.[15] The full detail of the reaction, including both production and decay angles, can be reconstructed. In particular, the W bosons at central values of the decay angle $\cos\theta$ are those with longitudinal polarization. By fitting the full multi-variable distribution, it is possible to obtain limits on the κ and λ parameters at the 10^{-3} level at 500 GeV, and even more stringent limits at higher energy.[16]

3.2 WW scattering

The principle that gives us access to the production amplitudes for states from the symmetry-breaking sector also allows us to study the interactions of these particles. In the reactions $e^+e^- \to \nu\overline{\nu}VV$, where VV is W^+W^- or Z^0Z^0, the most important subprocess is that in which the incoming electron and positron radiate a W^- and W^+, which then collide and scatter. One can show that a substantial fraction of the radiated W's are longitudinally polarized.[17] The scattering amplitudes for these bosons come directly from the symmetry-breaking interactions.

Experiments on these scattering processes are difficult both at the LC and at the LHC. At the LHC, one can radiate W's from quark lines, detect the final vector bosons using their leptonic decays, and apply a forward jet tag or other topological cuts to enhance the signal over background. At the LC, one can study vector bosons using their hadronic decay models, imposing a cut on the total transverse momentum of the VV system to remove background from two-photon processes. It is important to be able to separate W and Z on the basis of the 2-jet mass.[18] Table 1, taken from ref. 13, compares the capabilities of LHC and the LC for 100 fb^{-1} event samples and an assumed LC energy of 1.5 TeV. (A larger LC luminosity sample would allow the study to be done at somewhat lower energies.) A notable advantages of the LC is its extraordinary sensitivity to vector resonances, which show up as s-channel resonances in $e^+e^- \to W^+W^-$. The LC also has a unique advantage in its ability to study the reaction $W^+W^- \to t\overline{t}$,[19] a reaction that directly probes the coupling of the top quark to the symmetry-breaking sector.

3.3 Top quark

Finally, the LC can access a strongly-coupled symmetry breaking sector through precision studies of the heaviest Standard Model particle, the top quark. The pair production reaction $e^+e^- \to t\overline{t}$ may be studied either at threshold or at higher energy.

The Standard Model prediction for $e^+e^- \to t\overline{t}$, like the prediction for $e^+e^- \to W^+W^-$, has a rich structure. The production cross section depends strongly on both the electron and the t quark polarization. For example, the subprocess $e^-_L e^+_R \to t\overline{t}$ is dominated by forward production of t_L. The top polarization is visible because the short t lifetime guarantees that a produced t will not be depolarized by soft hadronic interactions,[20] and because the dominant decay $t \to bW^+$ and the subsequent W^+ decay have distributions sensitive to polarization. To take advantage of the final-state polarization observables, it is necessary to be able to reconstruct $t\overline{t}$ events efficiently in the 6-jet mode

Table 1: Estimated LHC and NLC sensitivity to resonances in the new strong interactions. For details, see ref. 13.

Machine	Parton Level Process	I	Reach	Sample	Eff. $\mathcal{L}$ Reach
LHC	$qq' \to qq'ZZ$	0	1600	1500^{+100}_{-70}	1500
LHC	$q\overline{q} \to WZ$	1	1600	1550^{+50}_{-50}	
LHC	$qq' \to qq'W^+W^+$	2	1950	2000^{+250}_{-200}	
NLC	$e^+e^- \to \nu\overline{\nu}ZZ$	0	1800	1600^{+180}_{-120}	2000
NLC	$e^+e^- \to \nu\overline{\nu}t\overline{t}$	0	1600	1500^{+450}_{-160}	
NLC	$e^+e^- \to W^+W^-$	1	4000	3000^{+180}_{-150}	

produced by hadronic W decays on both sides.[21]

In a theory with strong-coupling electroweak symmetry breaking, the top coupling to the strong sector shows up in its coupling to gauge bosons. Already in the Standard Model, 70% of the W^+'s from top decay are longitudinally polarized, reflecting the dominance of the top Yukawa coupling over the $SU(2)$ gauge coupling in top decays. This fraction may be enhanced in strong-coupling models. In technicolor models, the Z^0 coupling to third-generation quarks is predicted to be shifted by diagrams involving extended technicolor boson exchange. This effect is not seen in the $Z^0 \to b\overline{b}$ coupling. However, it is natural that effects which cancel in that coupling add constructively in the coupling to top, giving rise to shifts of up to 10% in the $Z^0 t\overline{t}$ coupling that would be revealed by the measurements of the polarization asymmetry for top production.[22] On the other hand, if there is a light Higgs boson, it should be possible to observe the process $e^+e^- \to t\overline{t}h^0$ and thus measure the $t\overline{t}h$ coupling directly.

It is also interesting to obtain as accurate as possible a value for the top quark mass, both because of the important role of virtual top quarks in phenomonology and because of its intrinsic interest for the problem of flavor. At a LC, the top quark mass can be computed from the position of the $t\overline{t}$ threshold. The energy region that, for lighter quarks, holds the bound quarkonium states is smeared out by the large top quark width. The resulting smeared shape can

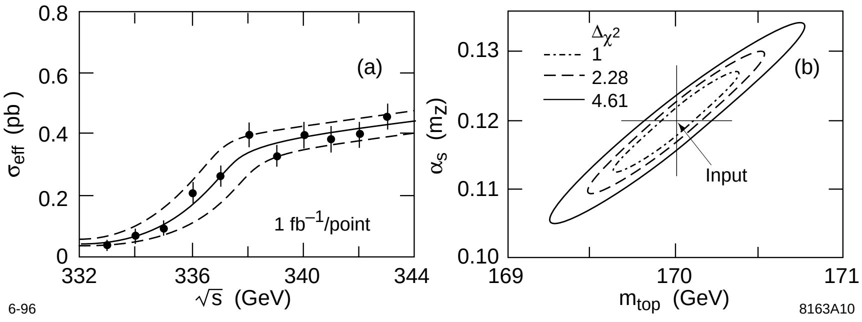

Figure 3: Measurement of the $t\bar{t}$ threshold location, from a simulation study by Sumino, ref. 23.

be computed accurately in QCD. The position of the threshold can be located to about 200 MeV with relatively small data samples (10 fb^{-1}), given an accurate value of α_s. The results of a simulation study are shown in Figure 3. The threshold position can be related to the short distance parameter $m_{t\overline{MS}}(m_t)$ with a similarly small error.[24]

4 Weak-Coupling Route to EWSB

The alternative class of models of electroweak symmetry breaking are those in which $SU(2) \times U(1)$ is broken by the vacuum expectation value of a weakly-coupled Higgs scalar field. In these models, there is a light Higgs boson, and possibly also a spectrum of heavier Higgs states. Since the precision electroweak data favor a low Higgs boson mass and also exclude large modifications of the $Zb\bar{b}$ coupling, it is this alternative which currently has the most experimental support. A Higgs boson in this mass range should be discovered before the LC experiments, at LEP 2 or the Tevatron and certainly at the LHC. However, it will be the LC that tests whether this particle indeed generates the quark, lepton, and gauge boson masses.

The simplest weak-coupling models do not explain why $SU(2) \times U(1)$ is broken. Rather, the symmetry-breaking is the result of a negative $(\mathrm{mass})^2$ parameter for the Higgs field that is inserted into the Lagrangian by hand. The only way to avoid this unsatisfactory situation without requiring strong coupling is to introduce a symmetry that links the Higgs field to some field of higher spin. This eventually requires that the theory of electroweak symmetry breaking be supersymmetric. Conversely, a supersymmetric generalization of the Standard Model easily generates a symmetry-breaking potential for the

Higgs field as the result of radiative corrections due to the heavy top quark. Thus, the assumption that EWSB has a weak-coupling origin leads naturally to supersymmetry.

Both aspects of the weak-coupling models have interesting implications for the LC. The light and heavy states of the Higgs boson spectrum can be studied in detail in e^+e^- annihilation. The LC also offers many incisive tools for the precision study of the spectrum of supersymmetric particles.

4.1 Higgs boson

One of the key aspects of the LC experimental program is the study of a light Higgs boson. Any Higgs boson with a mass below 350 GeV can be studied at a 500 GeV LC through the reaction $e^+e^- \to Z^0 h^0$. Though the Higgs boson is not produced at rest as a resonance, the experimental setting is extremely clean. The h^0 appears as a peak at a definite recoil energy, and our precise knowledge of the Z^0 mass and branching ratios can be used to establish the signal in a variety of h^0 decay modes.

The crucial question for a light Higgs boson is, does it couple to all species proportional to mass? To test this, one may check the relative Higgs branching ratios predicted by the Minimal Standard Model. The relative rates for b, c, and τ pairs (72%:3%:7% for $m_h = 120$ GeV) correspond to an identical scale for the Higgs couplings to down quarks, up quarks, and leptons. In multi-Higgs models, the lightest Higgs will typically couple preferentially either to up- or to down-type fermions. The coupling to WW and the total Zh production rate, which is proportional to the hZZ coupling, test the extent to which the W and Z masses that are due to the h^0. The branching ratios to gg and $\gamma\gamma$ measure sum rules over the colored and uncolored massive spectrum.[26] In Figure 4, I show a recent estimate of the accuracies that can be achieved in a variety of Higgs decay modes.[25]

The measurement of the $\gamma\gamma$ branching ratio or partial width from Zh production requires very large luminosity samples. Alternatively, this measurement is straightforward at a $\gamma\gamma$ collider and provides a strong physics motivation for developing that technology.[27,28]

There is no reason why a weakly-coupled Higgs sector should not contain several scalar fields whose vacuum expectation values contribute to the Z and W masses. Experiments at the LC can discover the complete set of these bosons and prove that they are fully responsible for the vector boson masses. To be specific, let the vacuum expectation value of the ith Higgs h_i^0 be $f_i v$, where $v = 246$ GeV. Then the h_i^0 is produced in recoil against the Z^0 with a cross section equal to a factor f_i^2 times the cross section for a Minimal Standard

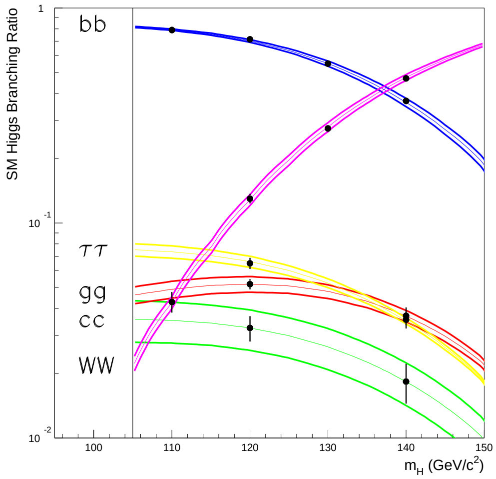

Figure 4: Measurement of the Minimal Standard Model Higgs boson branching ratios, from a simulation study by Battaglia, ref. 25, assuming 500 fb^{-1} at $E_{\text{CM}} = 350$ GeV.

Model Higgs of that mass. We have found the full set of scalars when the observed bosons saturate the sum rule[29]

$$\sum_i f_i^2 = 1 \; . \tag{2}$$

The ability of the LC to recognize the Higgs boson as a peak in the Z^0 recoil energy spectrum, independently of the Higgs decay mode, is crucial for this study.

Models with additional Higgs fields also contain additional heavy spin-0 states. Supersymmetric models, for example, typically contain heavy Higgs states that are pair-produced via $e^+e^- \to H^0A^0$, $e^+e^- \to H^+H^-$. The couplings of these states to fermion pairs are not universal among species but rather depend strongly on the underlying parameters of the Higgs sector. Thus, the branching ratios can be used systematically to determine these parameters, such as $\tan\beta$, which are needed as input in other aspects of the theory.[30]

4.2 Supersymmetry

I have explained above that supersymmetry is naturally connected to the idea of weak-coupling electroweak symmetry breaking. Many theorists (I am one) would claim that any plausible model with a light Higgs boson must contain supersymmetry at the TeV scale.

If supersymmetry is responsible for electroweak symmetry breaking, supersymmetric particles should be discovered at LEP2, the Tevatron, or the LHC before the LC experiments begin. Very clever methods have been devised to make precise mass measurements of supersymmetric particles at the LHC.[31] But nevertheless, there are intrinsic difficulties in studying supersymmetry at hadron colliders. It is not possible to determine the initial parton energies or, because of unobserved final particles, to reconstruct the complete final state. All possible supersymmetric particles are produced at once in the same event sample, so that individual particles must be separated on the basis of branching to characteristic decay modes.

The LC brings new tools that can clarify the nature of these new particles. First of all, since cross sections in e^+e^- annihilation depend in a model-independent way on the spins and $SU(2)\times U(1)$ quantum numbers of the produced particles, the LC can verify that new particles have the correct quantum numbers to be supersymmetric partners of Standard Model states. By adjustment of the center-of-mass energy and polarization, one can select specific states preferentially. An example is given in Figure 5, where the masses of the distinct supersymmetric partners of e^-_L and e^-_R are determined by the positions of kinematic endpoints observed in $e^+e^- \to \widetilde{e}^+\widetilde{e}^-$ with a polarized e^- beams.[32] A detailed analysis in which this strategy is used to make a precise spectrum measurement is presented in ref. 33. In systems where superpartners naturally mix—for example, the $\widetilde{t}_L, \widetilde{t}_R$ and $\widetilde{w}^+, \widetilde{h}^+$ combinations—the dependence on beam polarization can be used to measure the mixing angles. For the $\widetilde{\tau}$ and other states that decay to τ, the kinematic contraints allow final-state τ polarization to be used also as a powerful probe.[35]

These probes are needed because supersymmetry models are typically complex, with not only a doubling of the particle spectrum but also a number of new phenomena. As one example, I have already noted that, in models of supersymmetry, EWSB may arise as a byproduct of the renormalization of the scalar mass spectrum. We need to be able to measure the underlying parameters of responsible for this effect to see whether this in fact is the explanation for EWSB. In the simplest models, the masses derived from supersymmetry breaking are independent of flavor, but this is not necessary and must be tested directly. In Table 2, I have made a more complete list of issues that must be

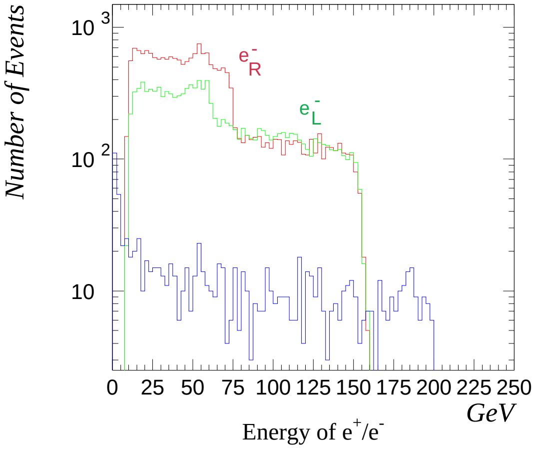

Figure 5: The electron and positron energy spectrum in $e^+e^- \to \widetilde{e}^+\widetilde{e}^-$, for beams with 80% e^-_L and e^-_R polarization, from a simulation study by Danielson and Goodman, ref. 32. The lower histogram represents the background from 2-photon processes.

probed experimentally before we can claim that we understand the supersymmetric generalization of the Standard Model. Underlying all of these issues is the question of the origin of supersymmetry breaking. This phenomenon, which supplies most of the new parameters of a supersymmetric model, would probably arise from energy scales far above 1 TeV. The understanding of the new parameters of supersymmetry could then potentially give us a window into physics at extremely short distances.[34]

4.3 Extra dimensions

Many people express the opinion that supersymmetry, with large number of postulated new particles, is too daring a generalization to be the true theory of the TeV scale physics. My own opinion is that it is not daring enough. Supersymmetric models require all of their complex components to explain the details in Nature which are missing from the Standard Model. But these components are not unified by a common underlying idea. Contrast with it the theory which is now understood for the GeV scale. Here experiment revealed a complex array of new states and couplings, but these turned out all to arise from the underlying simplicity of the Yang-Mills gauge interaction.

Recently, there has been much discussion of a grander idea for the nature of TeV-scale physics. For many years, string theory has suggested that space-time

Table 2: Questions for the experimental program on supersymmetry

- Is it really SUSY?
    - new particle quantum numbers, spin, statistics
    - identification of complete $SU(2) \times U(1)$ multiplets
    - SUSY relation of coupling constants
- Major spectrum parameters
    - gaugino/Higgsino mixing
    - gaugino mass ratios: $m_1 : m_2 : m_3$
    - flavor universality of $\widetilde{q}$, $\widetilde{\ell}_R$, $\widetilde{\ell}_L$ masses ?
    - $\widetilde{q} : \widetilde{\ell}_R : \widetilde{\ell}_L$ mass ratios
    - signatures of gauge- or anomaly-mediation
    - signatures of R-parity violation
- Third generation and EWSB
    - determination of μ, $\tan\beta$
    - mixing of L/R partners for $\widetilde{t}$, $\widetilde{b}$, $\widetilde{\tau}$
    - h^0 mass
    - H^0, A^0, H^+ masses and branching ratios
- Precision effects
    - $\widetilde{q}_L - \widetilde{q}_R$, $\widetilde{u}_R - \widetilde{d}_R$ mass differences
    - radiation corrections to coupling relations
    - slepton flavor mixing
    - phases in soft parameters, CP violation

has more than four dimensions. It is possible that the scale of these dimensions, or even the scale of quantum gravity, is as low as TeV energies.[36,37,38] In this picture, high-energy experiments would reveal not only supersymmetry but also the higher-dimensional spectrum with extended supersymmetry that characterize string theory at short distances.

As one might expect, theories with new space dimensions suggest new phenomena that could be discovered at high energy.[11,39] A low quantum gravity scale would allow gravitational radiation to be seen in high-energy collisions, both as missing-energy processes and as spin-2 contact interactions in fermion-fermion scattering. A TeV scale for new dimensions would imply recurrences of the Standard Model gauge bosons, which would appear as dramatic s-channel resonances. Some of these phenomena could be observed at the LHC, but many of the new effects would require the probes with beam polarization and precision measurement which are the domain of the LC.

5 Conclusions

The success of the Standard Model in accounting for the detailed properties of the strong, weak, and electromagnetic interactions leads us to focus attention on physics of electroweak symmetry breaking. At this time we do not know the what new physics is responsible for this symmetry breaking. But, in any scenario, physicists would look to the LC for tools essential to understanding the new phenomena. These include the ability to predict background cross sections precisely, to interpret signal cross sections unambiguously, to detect b, c, and τ with high efficiency, and to analyze the effects of polarization both in the initial state and in decays. The capabilities of the LC will allow us to characterize these new interactions in detail, and to uncover their origin.

Acknowledgments

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