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The Quest for New Phenomena

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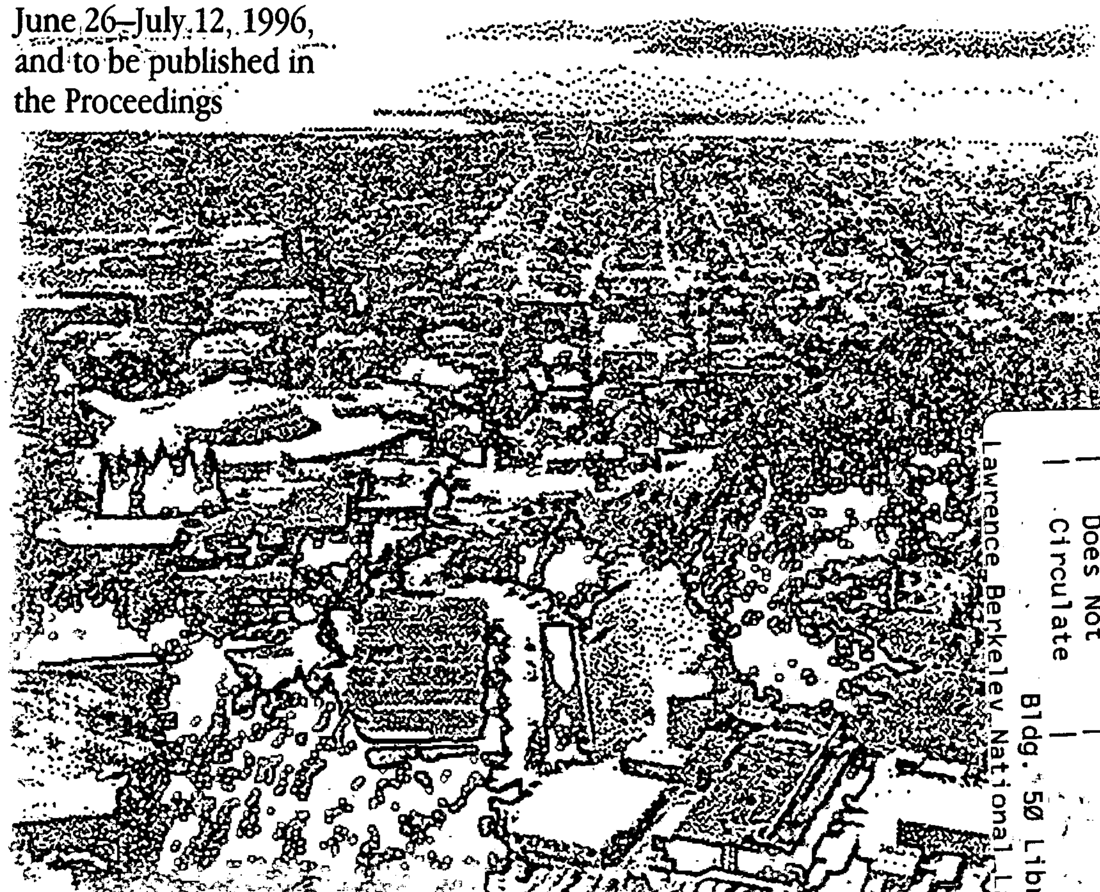

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The Quest for New Phenomena[1]

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Abstract

In this talk, I will compare the techniques used at, and capabilities of, various facilities in searching for new phenomena. I emphasise the cases where information from more than one facility may be needed to fully explore the physics.

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1 Introduction

The standard model [1]of particle physics has been very successful in describing experimental data with great precision; for more details see [2]. With the exception of some neutrino anomalies [3], there is no data that is in disagreement with it. Nevertheless, the model is regarded as incomplete and unsatisfactory. There is no explanation of the pattern of quark and lepton masses and, possibly more important, no understanding of the scale of electroweak interactions. Electroweak symmetry breaking is implemented in the standard model from the presence of a scalar electroweak doublet, the Higgs field, that acquires a vacuum expectation value of order 250 GeV and leaves as a remnant one physical state, the electrically neutral Higgs boson whose mass is not predicted.

The Higgs boson is unique in being the only elementary scalar particle in the standard model and being responsible for the masses of all particles. The key to understanding the dynamics of this sector is the ability to probe this *and any associated* particles. Should a Higgs-like boson be discovered, it is vital that enough of its properties (and those of its associated particles, if any) be measured so that different models of electroweak symmetry breaking can be eliminated. These models fall into two general classes; those, like the minimal standard model, where all electro-weak particles are weakly coupled, and those where the underlying mechanism of weak interaction symmetry breaking involves new non-perturbative dynamics. Supersymmetric models are the most popular manifestations of the first type of model. Here all particles have a partner of the opposite statistics (sparticles). The Higgs boson is now one of many scalar particles (the partners of the quarks and leptons, squarks and sleptons) and supersymmetry solves the famous hierarchy problem.

In the standard model, the mass of the Higgs boson and the scale of electroweak interactions is subject to very large radiative corrections which result in a natural value for these quantities that is the same as any higher scale (such as the scale where the model is unified into one with fewer parameters, the grand unified scale, or the scale where gravitational interactions become important, the Planck scale). Supersymmetric models are free of this difficulty provided that the partners have mass on the electroweak scale, and offer an additional tantalizing bonus, the possibility of a unified theory involving gravity. In addition to the presence of sparticles, a supersymmetric model must have at least three neutral and one charged Higgs boson.

The second type of model involves some new strong dynamics that trigger electroweak symmetry breaking, rather as chiral symmetry breaking is triggered by the strong interactions of QCD resulting in a (nearly massless) pion. In models of this type, it is more difficult to make definite predictions of the phenomenology since perturbative methods are not useful. Independent of the model, there must be strong interactions between the electroweak gauge bosons when they are scattered from each other at energies above 1 TeV. This model independent prediction is the hardest to test as it requires experiments at the very highest energies and luminosities. There could be many new exotic resonances that are easier to detect, but failure to find them would not eliminate this type of model.

I will now discuss how various facilities approach the detection of these signals. I will draw on the many detailed studies that have been performed. The capabilities of e^+e^- machines are easiest to discuss as they have a well defined energy threshold for the production of new particles. Particles that must be produced in pairs, such as new quarks, must have mass less than the beam energy and nothing can be produced that is heavier than twice the beam energy. LEP at CERN will have an ultimate energy of around 200 GeV and which will be reached in the next year or so. Several linear e^+e^- colliders are under active discussion with energies initially of ~ 250GeV per beam, rising ultimately to something in excess of 500 GeV per beam [4, 5, 6]. Event rates in lepton colliders are small. The figure of merit is a unit of R defined as a cross-section given by $1R = \frac{87\text{nb}}{s}$, where s is the center of mass energy squared in GeV^2. Most particles are produced with cross-sections of order 1 unit of R [7].

A consequence of this is that luminosity must rise with energy and luminosities in the range $5 \times 10^{33} \to 2 \times 10^{34}$ cm^{-2} sec^{-1} are needed as the center of mass energy rises from 500 GeV to 1.5 TeV. e^+e^- colliders have a powerful tool that can be used to disentangle new physics; beam polarization. Since electroweak interactions violate parity, rates for new particle production depend on the polarization of the incoming beams. Such machines could also be modified to be $\gamma - \gamma$ or $\gamma - e$ collider by the use of backscattered lasers. The former could be useful in exploiting the process $\gamma\gamma \to H$.

A more speculative type of lepton collider is now under consideration: a $\mu^-\mu^+$ collider[8]. This has the potential of being able to reach higher energy (as large as 4 TeV), but many problems, such as the potentially enormous detector backgrounds, have yet to be overcome. The physics potential of such a machine is similar to e^+e^- colliders of the same energy with one important exception; a muon collider may be able to see Higgs scalars produced as s-channel resonances $\mu^+\mu^- \to H$ as I will discuss below.

The Tevatron $p\overline{p}$ collider in its next run at $\sqrt{s} = 2$ TeV, scheduled to begin in 1999, should accumulate data in excess of 1 fb^{-1} extending its reach for new physics considerably. Further upgrades to its luminosity will ensure that it is the premier machine for new physics searches until the LHC turns on[9].

The LHC, a pp collider of 14 TeV center of mass energy is scheduled to begin operation in 2005[10]. Its initial luminosity of 10^{33} is expected to rise ultimately to 10^{34} cm^{-2} sec^{-1}. The number of interactions per crossing is significantly higher at this increased luminosity and some backgrounds are worse. For this reason, I will often refer to "Low" and "High" luminosity in the physics examples that I discuss[11]. There has been some discussion of higher energy proton proton machines[14]. I will not discuss the physics of these in any detail. Extrapolation from LHC energies together with some older studies[15] that included such energies can be used to estimate their capabilities.

I will now illustrate the complementarity and capabilities of these various facilities, using specific physics examples. It is important to bear in mind that while some of these examples may be more popular than others particularly in the theoretical community, there is, as yet, no evidence that conclusively favors one of them.

2 Higgs Physics

The properties of the minimal standard model Higgs boson are fully determined, once its mass is known. This makes it a particularly easy candidate for experimental simulation and partly explains why it has been so extensively studied. The best limit on its mass is currently 58.4 GeV from LEP[16], ultimately LEP will discover the Higgs boson via the process $e^+e^- \to ZH$ if its mass is below ~ 94 GeV [17]. Apart from the small window which may exist at the Tevatron (see below), if its mass is larger than this, its discovery will have to await one of the higher energy machines.

Higher energy lepton colliders can use one of two processes. $e^+e^- \to ZH$

dominates when $\sqrt{s}/M_H \lesssim 2.5$ but $e^+e^- \to \nu\overline{\nu}H$ has a cross section that grows like $\sim logs$ and dominates at larger values. For $M_H < 2M_W$ the intrinsic width of the Higgs boson is very small and its mass can be measured with a precision of order ± 200 MeV. In this range the branching fractions to $\tau\tau$, WW^* $b\overline{b}$ and gg can be measured with some precision in a lepton collider [18].

The Higgs boson affords an important exception to the rule that e^+e^- and $\mu^+\mu^-$ colliders are equivalent in their physics capabilities if they have the same energy and luminosity. Since the coupling of a Higgs boson to a fermion is proportional to the fermion's mass, the Higgs can be produced with sufficient rate to be observed as peak in the s-channel production process $\mu^+\mu^- \to H$. This would enable the Higgs width and mass to be measured directly[19].

At LHC, several channels can be used to search for the Higgs boson. At low masses the mode $\to \gamma\gamma$ can be exploited. The signal to background ratio is poor, due to the large rate for $q\overline{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$. Isolation cuts, requiring that the candidate photon is not accompanied by any nearby hadronic energy, can be used to bring reducible backgrounds from sources such as $qg \to \gamma + jet$ below these irreducible backgrounds. Excellent diphoton mass resolution is needed to see a signal; it is this process that drives the specifications for the electromagnetic calorimeters of both the ATLAS[12] and CMS detectors[13]. At high luminosity, the presence of multiple primary interactions, implies that the photon direction as well as its energy must be measured in order to reconstruct the diphoton invariant mass.

CMS has a mass resolution of order 540 (870) MeV at $m_H = 110$ for low (high) luminosity[20]. The mass resolution is worse at high luminosity due to event pile up and the presence of a preshower detector that is used to determine the photon direction. The preshower enables the photon direction to be determined with a precision of $40mr/\sqrt{E}$ and used to resolve the ambiguity in which of the several events contains the signal and therefore what point along the beam is used in computing the diphoton invariant mass. It is not present at low luminosity. The ATLAS mass resolution in at high (low) luminosity is 1.2 (1.1) GeV for at $M_H = 110$ GeV. However the photon acceptance and identification efficiency are higher in the ATLAS simulation[21], partly because CMS rejects photons that convert in the inner detector. In this mode LHC can discover the Higgs if its mass is too high to be detected at LEP and below about 140 GeV. At larger masses the branching ratio becomes too small for a signal to be extracted. If a Higgs boson has been found at LEP, the larger event rate at the LHC and the excellent resolution available should allow its mass to be measured more precisely there.

The search for the Standard Model Higgs at LHC relies on the four-lepton channel over a broad mass range from $m_H \sim 130$ GeV to $m_H \sim 800$ GeV. Below $2m_Z$ the event rate is small and the background reduction more difficult, as one or both of the Z-bosons are off-shell. In this mass region the Higgs width is small ($\lesssim$1 GeV) and so lepton energy or momentum resolution is of great importance in determining the significance of a signal[22]. For Higgs masses in excess of $2M_Z$, the signal to background ratio is excellent and the process is limited by event rate.

Other possible decays of a Higgs boson might be exploitable at a hadron collider. The decay $H \to b\bar{b}$ cannot be used due to background and triggering problems unless the Higgs is produced in association with other, triggerable, objects. WH and $t\bar{t}H$, final states can provide a trigger from the leptonic decay of the W or top quark. ZH has too low a rate if one relies on the leptonic decays of the Z; a global missing E_T trigger using the decay $Z \to \nu\bar{\nu}$ might make this mode usable also. The ability to tag $b-$ jets with an efficiency of order 50% while rejecting light quark and gluon jets at the 1% level is needed so that the background is dominated by $b-$quarks and not by fakes[24]. This rejection is similar to that achieved by CDF[25]; the LHC experiments should be able to achieve it, at least at low luminosity. For Higgs masses around 100 GeV, the LHC will probably be able to use this mode, at least to confirm the discovery of the Higgs in another channel and provide more information on its couplings. Given enough integrated luminosity, the Tevatron might also be able to observe this mode[9], perhaps confirming a discovery made at LEP.

For Higgs bosons of very large mass, it would be useful to exploit the decays $H \to WW \to e\nu + jet - jet$ which has a potentially larger rate. Detailed studies have concluded that this signal might be extractable from the very large $W + jets$ final state.

3 Non-Standard Higgs bosons

Once the Higgs sector is extended beyond that of the standard model, additional neutral and charged Higgs bosons appear that have model dependent decay modes. The process $e^+e^- \to ZH$ should be able to discover and measure the mass of H independent of its decay modes. Even if H decays to invisible final states, the combination of the reconstructed Z and the known center of mass energy is sufficient. The situation in hadron colliders is considerably more complicated.

Most of the discussion has focussed on Higgs bosons in the Minimal Supersymmetric standard model. Here there are three neutral and on charged Higgs boson. The lightest neutral boson (h) has a mass less than 130 GeV or so and behaves similarly to the standard model Higgs boson and the same modes can be used to search for it. Other channels can be exploited to search for the heavier neutral bosons A and H. These include $A \to \tau\tau$,[23] $A \to \mu^+\mu^-$[26], $A \to Zh$[13, 27]. Over much of the parameter space several modes are available, although several years of running at the full LHC luminosity may be needed to exclude the model over all of its possible range of parameters[27].

In order to carry out the simulations in detail, production cross sections and branching ratios need to be known. As radiative corrections are important for these [28], the full mass spectrum is needed, not just the masses of the particles being simulated. The model assumes that the supersymmetric particles are all very heavy so the possible decays of Higgs bosons to supersymmetric particles do not occur and their contributions to radiative corrections are irrelevant. This assumption may not be correct. In different scenarios branching ratios might be reduced making observation more difficult. However if supersymmetry is correct, supersymmetric particles will be discovered at LHC (see next section) and that facility not be dependent on the Higgs sector for much of its exciting physics. In addition the production rate for h could be enhanced as it is often the case that decays of squarks and gluinos can give rise to it. The full exploration of the Higgs sector in a supersymmetric model is likely to require a lepton collider of sufficient energy to produce all of the Higgs bosons.

4 Supersymmetry

A supersymmetric theory with masses for the partners of all the known particles in the range below 1 TeV or so would solve the naturalness problem of the scale of electroweak interactions and hold out the possibility of a grand unification of strong weak and electromagnetic interactions within a perturbative theory. If such a theory is true, it will be discovered at LEP, the Tevatron or LHC. Such a theory has a large number of new particles and we will to measure the masses and decay properties of all of them. Such a vast program is beyond the scope of any one facility. Rather than describe particular analyses in detail, I will make some general remarks.

The details of the signals for supersymmetric particles are model dependent[29], but the models can be grouped into three main classes. First those where all the supersymmetric particles decay to a set of quarks, leptons, gluons and a single stable neutral particle called the lightest supersymmetric particle (LSP) that then leaves the detector. This LSP may be a good candidate for the dark matter than is believed to pervade all of space. The supergravity models with R parity conservation are of this type[30]. These models have the classic signatures of jets and/or leptons accompanied by missing energy. The presence of two LSP's in the decay chain ensures that masses of SUSY particles cannot be measured by fully reconstructing the decays as, for example, the top quark can be reconstructed at the Tevatron.

In the second class of models the LSP is unstable. If it decays outside the detector, the signals are the same as in the first class of models. In Supergravity type models with R-parity broken, the LSP decays either to three leptons or three jets[31]. In the leptonic case, each SUSY event has four charged leptons and missing energy (one of the leptons from each decay must be a neutrino). In the jet case, the missing energy signature is lost, but the possibility of fully reconstructing events exists. In the recently repopularized models of low energy dynamical SUSY breaking the LSP decays into a photon and gravitino (which is stable and weakly interacting). All SUSY events then have an additional pair of photons and missing energy.

The third class of models is those where the LSP is unstable, but is charged. This can occur in the dynamical SUSY breaking models [32] where the supersymmetric partner of the tau lepton is the LSP, which then decays to a tau and a gravitino. If this decay takes place outside of the detector, then each SUSY event has a pair of heavy weakly interacting charged particles in it.

The great power of a lepton collider is its simplicity. All particles with electroweak couplings are produced with roughly the same rate and with a well defined energy. At LEP it is unlikely that more than a few supersymmetric particles would be produced and measuring their masses and decays should be straightforward. Several studies of possible searches at higher energy lepton colliders assume that that the energy is increased steadily so that the mass spectrum is revealed step by step. This makes the analysis very simple and clean[33]. In practice, I believe that this is not necessary. Running the machine at the highest available energy is likely to be the approach taken. If one is lucky enough to be above threshold for several SUSY particles, one will sort them out. The ability to polarize the beams provides a very powerful diagnostic tool as the scalar partners of, for example, the left and right handed electron may not be degenerate in mass. It should be possible to measure the masses of any supersymmetric particles that are pair produced to an accuracy of a few GeV.

At LHC, the situation could be considerably more complicated. Production rates for squarks and gluinos could be very large, depending on their masses. It is even possible that several triggers could be dominated by SUSY particle decays rather than by those of currently known particles. This potential bonanza has led some people to claim that while SUSY can be discovered, it will be almost impossible to sort out what you have. I believe that this is much too strong a statement. [2] Most studies have concentrated on the simplest case where the LSP is stable and neutral and have concentrated on establishing the maximum mass to which the LSP is sensitive rather than how well properties of SUSY particles can be measured[35].

These studies have demonstrated that backgrounds at LHC from the standard model or from detector effects can be controlled. In particular the dominant background for events with missing E_T arises from the decays of Z and W bosons and not from effects of cracks or other detector imperfections [37].

Detection of superpartners that have only electroweak couplings may be difficult at LHC unless they are produced in the decay of strongly interacting partilces. Productuon rates are small and jet vetos will be required to eliminated backgrounds [36].

At the Tevatron, the situation is somewhat different. Given the current limits on SUSY particles, the event rates that can be observed there are quite low. The cleanest final state is probably that of three leptons arising from the pair production of weak gauginos followed by their leptonic decay to the

[2] At the time of giving this talk, I could not substantiate this view. At the time of writing, I have the benefit of hindsight. Examples of possible precision measurements of SUSY at the LHC were revealed at this meeting [34]

LSP.

5 Dynamical Electroweak Symmetry Breaking

If the Electroweak scale is generated dynamically by interactions among some new particles, there might be no weakly coupled Higgs bosons. The absence of a fully realistic model implementing this idea makes detailed phenomenology difficult. Technicolor models can be used for guidance[38]. All models of this type will reveal themselves by showing structure in the scattering amplitudes of electroweak gauge bosons which is not present in the weakly coupled standard model[39]. This model independent signal is also the most difficult to observe as the structure appears only when the center of mass energy of a diboson system is ($\gtrsim$1 TeV). The LHC and a lepton collider of center of mass energy of 1.5 TeV have approximately equivalent power for this physics and, at either, extraction of the underlying physics will be exceedingly difficult.

At LHC, experiments must be performed at the highest luminosity and the large background of diboson pairs from processes such as $q\overline{q} \to WW$ overcome. The channel with the least background is W^+W^+ which must be detected via its decay into two isolated same sign leptons and missing E_T. The physics process of interest is $qq \to qqWW$, so the WW system is accompanied by two jets of large rapidity. A tag requiring the presence of forward-going jets is essential to extract the signal. The process is periferal, so that the central part (in rapidity) of the event is relatively quiet. A veto, requiring that there be no central jets, is needed to extract a signal above the background. Several simulations done for LHC indicate that, if these requirements can be met, a signal can be extracted [40]. A significant background to the W^+W^+ final state arises from the WZ final state where one lepton from the Z is lost; the large WZ rate compensates for the small probability that a lepton is lost.

At a lepton collider, the signal to background ratio, before cuts, is much better but again the event rates are low. Here one will attempt to reconstruct the gauge bosons via their hadronic final states. At a collider of energy 1.5 TeV, an integrated luminosity in excess of 100 fb^{-1} is needed to extract a signal[41]; of order 100 signal events can be expected. Under such circumstances it may be possible to distinguish between different models by comparing event rates in different final states where the signal to background ratios are different. Beam polarization is again useful.

It is possible, perhaps even likely, that the particular dynamical model chosen by nature will have signals that are much easier to extract than in the most conservative case. These signals could involve the detection of narrow resonances in gauge boson pair final states. While these resonances are likely to have masses in excess of 1 TeV and hence small production rates, if they are narrow an unambiguous signal could be seen. An example is the so called techi-omega that would decay to a $Z\gamma$ final state and have a small width. It could be detected at LHC in the $\ell^+\ell^-\gamma$ final state above a rather small background [12]. States with mass less than 1 TeV are also possible. If these have strong interactions, then they will be produced in hadron colliders and LHC or even the Tevatron should see them[38].

Possible indirect effects of a strongly coupled gauge boson system may manifest themselves in small deviations from expected event rates. For example, detailed measurements of the gauge boson self couplings at lower energies may reveal values that are inconsistent with those of the standard model. For example, the $WW\gamma$ vertex may reveal deviations from the standard model values at the $\lesssim 1\%$ level from new physics at a strongly coupled sector at higher scale [42] or from the effects of new particles in, for example, a supersymmetric model [43]. By studying WW pair production in e^+e^- annihilation or $W\gamma$ final states in a hadron collider, the vertex can be constrained. The expected sensitivities for a 500 GeV lepton collider [44] and the LHC[45] are similar in this case. An observation of this type, while it would show that the standard model was incomplete, could be very diffficult to interpret.

6 Concluding Remarks

There are many other physics topics that I have not had time to discuss, I would like to conclude with some general remarks.

While the standard model of particle physics is remarkably successful, it is clearly incomplete. The scale of electroweak symmetry breaking is unexplained; no insight is given into the pattern of quark and lepton masses, and experimental verification of its predicted CP violation is incomplete.

The last of these issues will be explored at the $B-$factories now under construction[46]. It is difficult to plan facilities that address the second since we do not have reliable arguments for the appropriate energy scale.

Very general arguments that do not depend on the details of any particular theoretical model indicate the energy range of 100 GeV - 1.5 TeV as that where the mechanism responsible for electroweak symmetry breaking will manifest itself. The energy reach of current facilities, notably LEP and the Tevatron collider, is such that we are beginning to probe this range. Results from these facilities should be able to eliminate some of the current theoretical options and perhaps suggest which of the remaining ones is favored.

The only approved facility that aims to cover the full energy range is the LHC. We do not know how much of the mechanism and its manifestations the LHC will reveal and it is therefore difficult to be certain what other facilities will contribute. Several things are, however, clear. The production rate for particles that do not have strong interactions is relatively low at LHC unless these particles are produced in the decay of other strongly interacting particles. Since, in some theoretical options, the strongly interacting particles are heavier, lepton collider (LC) with somewhat less usable energy than the LHC should be able to provide significant additional information. A concrete example of this type of option is a supersymmetric model where squarks and gluinos are often significantly heavier than sleptons.

General arguments of this type lead one to the conclusion that it is possible and even likely that while the LHC will provide great insights and possibly suggest the correct model of electroweak symmetry breaking, more information will be needed to complete the picture. A lepton collider of sufficiently high energy should be able to provide this additional information. What "sufficiently high energy" means is not yet clear. If LEP2 or the Tevatron discovers new physics, then a lepton collider of center of mass energy of 500-700 GeV could be sufficient to elucidate, together with, LHC a great deal of the new physics. In the absence of such a discovery we must look to theoretical models for guidance.

If supersymmetry is correct, LHC will discover it and measure many of its properties, particularly of gluinos, squarks and particles produced in their decays. We would like to investigate the Higgs sector of such a theory. The LHC is likely to have a difficult time with the heavier Higgs bosons. A lepton collider is the ideal place to study them. In this case an energy of at least

1.5 TeV could be needed. The desire to probe the properties of the heavier electroweak gauginos that may not be produced in the decays of gluinos and squarks also drives one to the same energy range.

If electroweak symmetry breaking involves some new strong dynamics, its presence is likely to be revealed by the LHC operating at its full design luminosity. In this case, again, a lepton collider in the 1.5 - 2 TeV energy range is likely to provide significant additional information on the dynamics of strong WW scattering. If such a model turned out to be true, there would be an immediate motivation and strong argument for the next energy scale where the many resonances of the new strong dynamics would lie. In this case, the need for a significantly higher energy lepton or hadron collider would be strongly indicated.

This statements should not be taken to imply that at lower energy lepton collider is uninteresting, but the large investment needed to bring such a facility to completion would make the approval of a machine that, during its construction phase, was revealed to be of too low an energy, seem like a tragic mistake to those involved in it.

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