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PARTICLE PHYSICS RESEARCH AT A 500 GEV e$^+$e$^-$ LINEAR COLLIDER*

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ABSTRACT

The physics opportunities at an e$^+$e$^-$ linear collider operating at a center–of–mass energy of 500 GeV are reviewed.

I. INTRODUCTION

Research and development on e^+e^- linear colliders at SLAC, KEK, DESY and Novosibirsk has been progressing rapidly. One or more of these laboratories may, within a few years time, produce a conceptual design report for an e^+e^- linear collider with 500 GeV center–of–mass energy. A comprehensive discussion of the accelerator technology issues of such a machine can be found in another contribution to this conference[1]. In this paper we present a broad overview of the particle physics potential of a 500 GeV e^+e^- linear collider. We shall refer to a 500 GeV e^+e^- linear collider as the "next linear collider" or NLC.

We assume for most of the studies that the differential luminosity is between 10^{32} and 10^{33} cm^{-2} s^{-1}. The center–of–mass energy is usually taken to be 500 GeV, although for some studies the energy is lower. For example, the center–of–mass energy is dropped to 300 GeV for top threshold studies and is lowered to 114 GeV to study the $\gamma\gamma$ partial width of a 90 GeV Higgs boson.

II. THE TOP QUARK

Measurements[2] of the Z mass, the Z partial width to lepton pairs, and the W/Z mass ratio now restrict the top quark mass to the range 137 GeV $\pm$ 40 GeV through electroweak radiative corrections. If there is not a top quark within three sigma of 137 GeV (in particular, if there is not a top quark with mass less than 250 GeV) then there must exist another object with mass less than about 250 GeV which plays the role of the top quark in electroweak radiative corrections. It is therefore a consequence of present day electroweak measurements that top quark physics, or its substitute, is a guaranteed subject of study for the NLC.

There is no reason to believe that top quark physics will not be as rich and rewarding as the charm and bottom physics programs of the 1970's and 1980's. Not just quantitatively, but qualitatively, the top quark is unlike any quark physicists have studied. A 150 GeV top quark, for example, is almost twice the mass of the W boson, and is so massive that its Yukawa coupling, λ_t, is almost equal to one:

$$\lambda_t \equiv \frac{\sqrt{2}M_t}{\langle\Phi\rangle} = .85,$$

where M_t denotes the top quark mass and $\langle\Phi\rangle = 250$ GeV is the Higgs vacuum expectation value. A 150 GeV top quark is expected to decay predominantly through the Cabibbo enhanced two body channel $t \to bW^+$, and is expected therefore to have a very short lifetime. In fact, the lifetime of the top quark will be so short that it will decay before it hadronizes.

Peskin and Strassler[3] have studied the many interesting effects associated with top quark production near $t\bar{t}$ threshold. For large top masses, the toponium resonance decays predominantly to $b\bar{b}W^+W^-$, and, for top quark masses greater than about 150 GeV, this decay proceeds so rapidly that the toponium resonance begins to disappear. Peskin and Strassler point out that while the $t\bar{t}$ threshold region may not contain a series of resonances, it nevertheless will be a very interesting region to study. In particular, the behavior of the $t\bar{t}$ cross-section in the threshold region is governed by a variety of parameters and phenomena including the top mass, the total top decay width, the strong coupling constant, and the Higgs boson couplings of the top quark.

If the top has a mass of 150 GeV then 10,000 $t\bar{t}$ pairs will be produced per year if the NLC luminosity is $10^{33}cm^{-2}s^{-1}$ and the center–of–mass energy is set a little bit above $t\bar{t}$ threshold at 310 GeV . Among the top quark parameters which can be measured at the NLC are the top mass, the top width, and the top decay branching fractions.

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It has been estimated[4] that a top quark mass measurement of about 2 or 3 GeV will be required to test the electroweak radiative corrections of the Standard Model, given the expected precision of $\sin^2\theta_W$ in the late 1990's. SSC experiments are expected to measure the top quark mass with an accuracy of approximately 10 to 15 GeV.

S. Komamiya[5] has found that a measurement of the $t\bar{t}$ cross–section in the $t\bar{t}$ threshold region yields a top quark mass measurement with a resolution of better than 1 GeV with only $1fb^{-1}$ of luminosity. Given that the $t\bar{t}$ cross-section in the threshold region depends on so many parameters, it would be desirable to have an independent measurement of the top quark mass. At center-of-mass energies well above $t\bar{t}$ threshold it should indeed be possible to obtain such a top quark mass measurement, with an accuracy of better than 0.5 GeV, using beam energy constraints.

The NLC is an ideal machine to study top quark decays. Top quark events are cleanly separated from other processes by tagging the isolated lepton from a semi-leptonically decaying top quark. A very good measurement of $\Gamma(t \rightarrow bW^+)$ should be possible; it remains a topic of future study to determine how well the Cabibbo suppressed decay $\Gamma(t \rightarrow sW^+)$ can be measured. Interesting limits can be placed on the partial decay widths for top decays to a charged Higgs ($t \rightarrow bH^+$) and to the supersymmetric partner of the top ($t \rightarrow \tilde{t}\tilde{\chi}_1^0$). It will also be interesting to search for the flavor–changing neutral current decays $t \rightarrow c+\gamma,\ c+Z,\ c+H^0$.

Because the top quark decays before it hadronizes, the final state top quark polarization will not be lost to the hadronization process. Top quark production at the NLC can therefore be used to test Standard Model predictions which depend on the final state quark polarizations. For example, QCD radiative corrections are predicted[6] to generate nonzero quark polarizations transverse to the production plane when the quarks q are produced via $e^+e^- \rightarrow \gamma, Z \rightarrow q\bar{q}$.

III. GAUGE BOSON INTERACTIONS

While the interactions of gauge bosons with fermions have been extensively studied throughout this century, the interactions of gauge bosons with each other have received scant experimental attention. This is not due to lack of interest but rather to the large center–of–mass energies required to produce multiple gauge bosons.

Experiments at HERA, LEP II and the Tevatron will soon be testing the Standard Model predictions for gauge boson interactions. These experiments will improve the limits on anomalous gauge boson couplings, but they are really only the beginning. Machines at higher energies, such as the SSC and NLC, are required to test anomalous gauge boson couplings at the level of Standard Model radiative corrections. We shall see that the anomalous gauge boson limits from a 500 GeV NLC are significantly better than the limits from LEP II. We'll also see that the NLC limits are as good as the limits from the 40 TeV SSC for the parameters which are accessible to the SSC, and that the NLC can set limits on many parameters which are inaccessible to the SSC.

A. Three Gauge Boson Couplings

It has become common practice[7] to parametrize the general Lorentz invariant, C invariant, and P invariant triple gauge boson vertex VW^+W^- with the form factors κ_V and λ_V, where V denotes either a γ or a Z. With this parametrization the magnetic dipole moment μ_W and electric quadrupole moment Q_W of the W boson are given by

$$\mu_W = \frac{e}{2M_W}(1+\kappa_\gamma+\lambda_\gamma),$$

$$Q_W = -\frac{e}{M_W^2}(\kappa_\gamma-\lambda_\gamma) \quad .$$

In the Standard Model, at tree–level, $\kappa_V = 1$ and $\lambda_V = 0$, $V=\gamma, Z$.

The current limits on the individual κ_V and λ_V parameters from unitarity constraints and radiative corrections are surprisingly weak. Kane *et al.*[8] have found that these limits are no better than

$$\begin{array}{ll} |\lambda_\gamma| \leq 0.6 & |\kappa_\gamma - 1| \leq 1.0 \\ |\lambda_Z| \leq 0.6 & -0.8 \leq \kappa_Z - 1 \leq 0.0 \end{array}$$

The current limits on certain combinations of these variables are better, however. For example, $|\lambda_\gamma - \lambda_Z| < 0.1$ for all $\lambda_{\gamma,Z}$ and $|\lambda_\gamma - \lambda_Z| < 0.01$ for $|\lambda_{\gamma,Z}| > .25$. The allowed values of κ_γ and κ_Z form a thin ellipse in the κ_γ–κ_Z plane, as described in Ref. 8.

To set better limits on the form factors κ_V and λ_V, pairs of gauge bosons must be produced and studied. We remind the reader that tree–level unitarity is violated at high energies in processes such as $e^+e^- \rightarrow W^+W^-$ if the couplings at the γW^+W^- and ZW^+W^- vertices are anything but the ones dictated by the spontaneously broken SU(2)$\times$U(1) gauge symmetry. It is therefore advantageous to produce the gauge bosons at as high an energy as possible, everything else being equal.

By studying the processes $q\bar{q} \rightarrow W^+\gamma$ and $q\bar{q} \rightarrow W^+Z$, an upgraded Tevatron with 1 fb^{-1} integrated luminosity can set limits[8] of

$$|\lambda_\gamma| \leq 0.2 \qquad -0.50 \leq \kappa_\gamma - 1 \leq .80$$
$$|\lambda_Z| \leq 0.4 \qquad -0.80 \leq \kappa_Z - 1 \leq 0.0 \ .$$

LEP II, operating at constituent center–of–mass energies lower than the Tevatron, should be able to constrain[8] κ_V and λ_V to

$$|\lambda_\gamma| \leq 0.4 \qquad -0.14 \leq \kappa_\gamma - 1 \leq .87$$
$$|\lambda_Z| \leq 0.4 \qquad -0.24 \leq \kappa_Z - 1 \leq 0.0$$

For a 400 GeV center–of–mass NLC, Kane *et al.* predict that the following limits can be achieved by studying $e^+e^- \rightarrow W^+W^-$ with a luminosity of 5 fb^{-1}:

$$|\lambda_\gamma| \leq 0.1 \qquad -0.15 \leq \kappa_\gamma - 1 \leq .35$$
$$|\lambda_Z| \leq 0.1 \qquad -0.08 \leq \kappa_Z - 1 \leq 0.0$$

Note that in most instances the NLC limit is an improvement of a factor of four over the LEP II limit, even though the center–of–mass energy at a 400 GeV NLC is only a factor of two greater than LEP II.

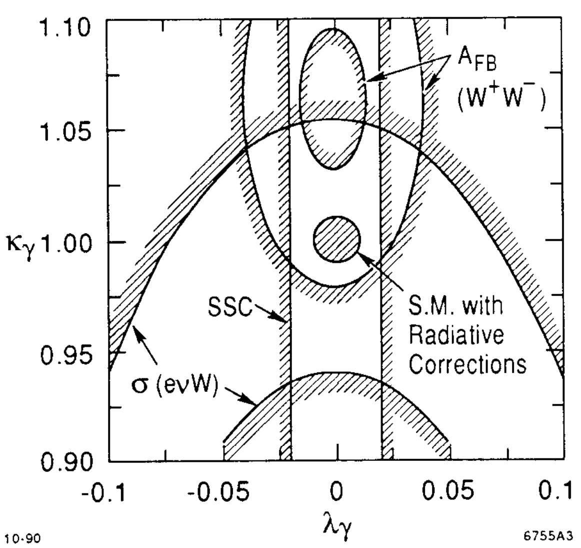

Fig. 1. Limits on κ_γ and λ_γ from $e^-\gamma \rightarrow W^-\nu$, from $e^+e^- \rightarrow W^+W^-$, and from the SSC.

E. Yehudai[9] has studied the limits that can be obtained at a 500 GeV center–of–mass energy NLC if the cross–section for $e^-\gamma \rightarrow W^-\nu$ is measured. The γ can come either from classical bremsstrahlung radiation by an e^+ (described by the Weizsäcker–Williams spectrum) or from radiation by an e^+ in the collective field of the e^- bunch (beamstrahlung). The process $e^-\gamma \rightarrow W^-\nu$ has the advantage over $e^+e^- \rightarrow W^+W^-$ in that (1) it is sensitive only to κ_γ and λ_γ and (2) many systematic errors cancel when the rate for $e^-\gamma \rightarrow W^-\nu$ is normalized to the rate for Compton scattering. Yehudai's results for 10 fb^{-1} integrated luminosity are shown in Figure 1, along with the expected results from $e^+e^- \rightarrow W^+W^-$.

The expected limit[8] on λ_γ from an SSC experiment with 10 fb^{-1} is also shown in Figure 1. The limit on κ_γ from the SSC is only $|\kappa_\gamma - 1| < 0.1$, and so the SSC κ_γ limit coincides with the upper and lower boundaries of Figure 1. Note that the area of the NLC allowed region is smaller, by about a factor of two, than the area of the SSC allowed region. For reference, the contribution to κ_γ and λ_γ from one–loop radiative corrections is also shown in Figure 1.

In a paper contributed to this conference[10], Couture, Godfrey, and Lewis have investigated how the process $e^+e^- \rightarrow \nu\bar{\nu}Z$ can be used to study κ_Z and λ_Z at the NLC. They have also looked at $\gamma\gamma \rightarrow W^+W^-$ as a means to set limits on κ_γ and λ_γ, where the photons in the initial state are produced by backscattering laser light off both charged particle beams. Although their results are not yet in a form that can be directly compared with the limit estimates of Kane *et al.*, the approaches of Couture *et al.* nevertheless look very encouraging.

B. Four Gauge Boson Couplings

The SU(2)×U(1) theory, being a non–Abelian gauge theory, predicts nonzero tree–level couplings for vertices with *four* gauge bosons. In particular, there are nonzero tree–level couplings for the vertices $W^+W^-\gamma\gamma$, $W^+W^-\gamma Z$, W^+W^-ZZ, and $W^+W^-W^+W^-$.

To test these couplings it is necessary to produce and detect three gauge bosons in the final state. LEP II has only enough energy to produce the final state $W^+W^-\gamma$, and even then the process is too close to threshold to be of any value. The SSC will produce many events with three gauge bosons in the final state, but it is probably too difficult to isolate these events given the SSC experimental environment. The NLC, on the other hand, is far enough away from threshold to produce many $W^+W^-\gamma$ and W^+W^-Z events, and, it should be possible to isolate a large fraction of these events in the clean environment of an e^+e^- collider.

The cross-section[11] for $e^+e^- \rightarrow W^+W^-Z$ is .039 pb at $\sqrt{s} = 500$ GeV, ignoring any enhancement in the cross-section from Higgs boson production. At least 390 W^+W^-Z events will therefore be produced per year at a luminosity of $10^{33} cm^{-2} s^{-1}$. For Higgs masses between 160 and 400 GeV there is an enhancement in the cross–section for $e^+e^- \rightarrow W^+W^-Z$ from real Higgs production followed by the decay of the Higgs to W^+W^-. This enhancement reaches a maximum of 18% at a Higgs mass of 250 GeV.

Note that the presence of a Higgs boson could complicate the measurement of the quartic $WWZZ$ and $WWZ\gamma$ gauge boson couplings. However, it should be straightforward to deal with this "problem" since the Higgs contribution will show up as a resonance in the WW invariant mass plots for WWZ events and in the ZZ invariant mass plots for ZZZ events. The same Higgs boson will also be produced in WW fusion ($e^+e^- \rightarrow \nu\bar{\nu}H^0$).

The $WWZ\gamma$ and $WW\gamma\gamma$ quartic couplings can be tested through the process $e^+e^- \rightarrow W^+W^-\gamma$. For final states in which the γ makes an angle of greater than 15° with respect to the beam axis and in which the P_T of the γ is greater than 20 GeV, the cross section[11] for $e^+e^- \rightarrow W^+W^-\gamma$ is 0.14 *pb*. 1400 such events will therefore be produced per year at an NLC with a luminosity of $10^{33} cm^{-2} s^{-1}$.

IV. HIGGS BOSONS

If Higgs bosons are elementary particles, rather than composite objects, then most extensions to the Standard Model favor Higgs bosons with masses less than about 250 GeV. For example, grand unified theories place upper bounds[12,13] of $\approx$ 200 GeV on the masses of Higgs bosons under the assumptions that there is no new physics between the electroweak scale and the grand unification scale, and that the strong and electroweak interactions remain perturbative up to a grand unification scale $M_U \geq 10^{14}$ GeV. Another example is supersymmetry. In the minimal supersymmetric extension to the to the Standard Model[14] there must be at least one Higgs scalar with a tree–level mass less than the Z mass. Recently, theorists have discovered[15,16] that radiative corrections may push the mass of this lightest Higgs boson to 120 or 130 GeV, well beyond the envisioned reach of LEP II.

A third example is the class of theories in which the top quark is responsible for electroweak symmetry breaking[17]. In such models the Higgs boson is a $t\bar{t}$ condensate and the Higgs mass is predicted to lie in the range $M_t < M_{H^0} < 2M_t$. Although the Higgs boson is not, strictly speaking, an elementary particle in such theories, it is so tightly bound that it is effectively an elementary particle at the energy scales we are considering.

A 500 GeV center–of–mass e^+e^- linear collider can study in detail the complete spectrum of Higgs scalars with masses less than about 250 GeV . In addition, it may be possible to extend the Higgs mass reach of such a collider to 400 GeV by colliding beams of backscattered laser photons.

A. The Minimal Standard Model Higgs Boson

We begin our survey of NLC Higgs physics with the minimal Standard Model Higgs boson, which we shall denote by ϕ^0. If the SSC has trouble searching for Higgs bosons with masses less than 200 GeV, then the mass range between the LEP II limit (80 to 90 GeV) and 200 GeV will be explored first with the NLC. As was shown at the 1988 Snowmass study[18], an e^+e^- collider with a 400 GeV center–of–mass energy and luminosity $10 fb^{-1}$ can readily detect the ϕ^0 if its mass is less than about 200 GeV. Once discovered, the ϕ^0 can be studied at the NLC by measuring the ϕ^0 partial widths $\Gamma(\phi^0 \rightarrow W^+W^-, ZZ, t\bar{t}, b\bar{b}, c\bar{c}, \tau^+\tau^-, \gamma\gamma)$.

In a paper contributed to this conference[19], T. Tauchi *et al.* show how the partial width $\Gamma(\phi^0 \rightarrow t\bar{t})$ can be measured by studying the reaction $e^+e^- \rightarrow Z\phi^0$. This is a complex final state when the ϕ^0 decays to $t\bar{t}$, and it is especially complicated when the $t, \bar{t}$ and Z all decay hadronically. Tauchi *et al.* nevertheless demonstrate that the totally hadronic final state can be successfully isolated in the environment of the NLC.

B. $\gamma\gamma$ Partial Width

By colliding two beams of laser light which have been backscattered off the e^- and e^+ beams of an e^+e^- linear collider, the partial width $\Gamma(\phi^0 \rightarrow \gamma\gamma)$ can also be measured. The $\gamma\gamma$ partial width of a Higgs boson[20,21] is of special interest because it receives contributions from all electrically charged elementary particles which couple to the particular Higgs boson. An elementary particle's contribution to the $\gamma\gamma$ partial width of the ϕ^0, for example, approaches a nonzero asymptotic value as the mass of the elementary particle approaches infinity. A measurement of the $\gamma\gamma$ partial width of the ϕ^0 can therefore probe physics at very large energy scales.

As this is a subject which is new to many readers we will digress from our broad overview of NLC physics and discuss in detail the question of measuring $\Gamma(\phi^0 \rightarrow \gamma\,\gamma)$ at the NLC.

The idea of compton scattering laser light off the e^- and e^+ beams of a single pass e^+e^- collider was first discussed by C. Akerlof[22] and I. Ginzburg *et al.*[23]. A laser photon can receive a substantial fraction of an electron's energy in the Compton scattering process.

For the electron and laser energies we are considering, the laser beam essentially splits the electron beam into two beams: an electron beam with an energy of about 20% of the original electron beam, and a photon beam with an energy of about 80% of the original electron beam.

The angular spread from the Compton collision process is small compared to the intrinsic angular spread of the original electron beam. The high energy photon beam therefore has the same cross-sectional area as the unscattered electron beam at the interaction point, so long as the laser conversion point is not too far from the interaction point. Given the small cross-sectional area of e^- beams near the interaction point of a linear collider, the laser power required to Compton scatter 99% of the electrons is modest: about 1 Joule per pulse with a pulse width of 1 picosecond and a pulse rate of about 100 Hz.

At first sight, it does not appear to make any difference whether the laser light is scattered off of colliding e^+e^- or e^-e^- beams. However, given the added complication of producing positron beams and the possibility that we may want to polarize both charged particle beams, we shall assume that the laser light is always Compton scattered off of colliding e^-e^- beams.

Figure 2 shows the $\gamma\gamma$ luminosity spectrum for doubly back-scattered laser light and for the more familiar virtual $\gamma\gamma$ collision process. The quantity plotted is

$$\frac{1}{L_{ee}}\frac{dL_{\gamma\gamma}}{dz}$$

where L_{ee} is the e^-e^- luminosity and $L_{\gamma\gamma}$ is the $\gamma\gamma$ luminosity. z is defined according to

$$z \equiv \frac{M_{\gamma\gamma}}{2E_b}$$

where $M_{\gamma\gamma}$ is the $\gamma\gamma$ invariant mass and E_b is the electron beam energy. The dotted line is the Weizsäcker–Williams spectrum for virtual $\gamma\gamma$ collisions. The dashed and solid lines show the backscattered laser luminosity spectrum for electron beam polarizations of 0% and 90% respectively.

In Figure 2 we've assumed that the laser beams have 100% circular polarization, and that the helicities of the laser and electron beams have opposite signs. The $\gamma\gamma$ luminosity spectrum also depends on the invariant mass of the electron and the laser photon. This invariant mass is often expressed in terms of the parameter x, defined by

$$x \equiv \frac{4E_b\omega_0}{m_e^2}$$

where ω_0 is the laser photon energy and m_e is the electron mass. The backscattered laser luminosity spectra in Figure 2 is shown for $x = 4.82$.

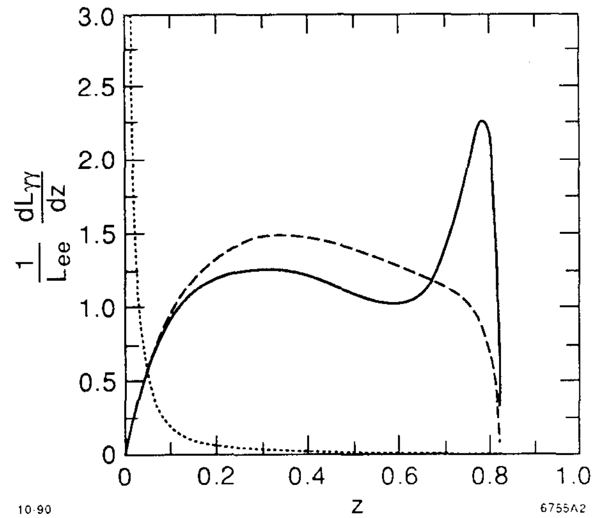

Fig. 2. Differential $\gamma\gamma$ luminosity for virtual $\gamma\gamma$ collisions (dotted line) and for backscattered laser photons with 0% e^- polarization (dashed line) and 90% e^- polarization (solid line).

From Figure 2 we can see the advantage of using backscattered laser light to study $\gamma\gamma$ collisions. At the value of z for which the solid curve in Figure 2 is a maximum ($z = .785$), the Weizsäcker–Williams differential luminosity is

$$\frac{1}{L_{ee}}\frac{dL_{\gamma\gamma}}{dz} = .001$$

while the backscattered laser differential luminosity (90% electron polarization) is

$$\frac{1}{L_{ee}}\frac{dL_{\gamma\gamma}}{dz} = 2.3$$

or 2,300 times the Weizsäcker–Williams luminosity.

The cross–section for $\gamma\gamma \to \phi^0$ is given by

$$\begin{aligned}\sigma(\gamma_1\gamma_2 \to \phi^0) &= \frac{8\pi\Gamma_{\gamma\gamma}\Gamma_{tot}}{(s - M_{\phi^0}^2)^2 + \Gamma_{tot}^2 M_{\phi^0}^2}(1 + \xi_1\xi_2) \\ &\approx \frac{4\pi^2\Gamma_{\gamma\gamma}}{M_{\phi^0}^3}(1 + \xi_1\xi_2)z_\phi\delta(z - z_\phi)\end{aligned}$$

where $\Gamma_{\gamma\gamma}$ is the $\gamma\gamma$ partial width of the Higgs, Γ_{tot} is the Higgs total decay width, M_{ϕ^0} is the mass of the Higgs, ξ_1 and ξ_2 are the mean helicities of the two photon beams, $s = 4E_b^2$, and

$$z_\phi \equiv \frac{M_{\phi^0}}{2E_b} \quad .$$

The total decay width of a Standard Model Higgs boson is only a few MeV for Higgs masses below the threshold for Higgs decay to W pairs ($M_{\phi^0} <$ 160 GeV). The delta function approximation of the Higgs cross–section is therefore a good approximation in this mass range. In the following we shall only consider Higgs masses less than 160 GeV.

The number of Higgs bosons produced is

$$\begin{aligned} N_{\phi^0} &= L_{ee}\int_0^{z_{max}} \left(\frac{1}{L_{ee}}\frac{dL_{\gamma\gamma}}{dz}\right)\sigma(\gamma\gamma \to \phi^0)dz \\ &= \frac{4\pi^2\Gamma_{\gamma\gamma}L_{ee}\Omega(z_\phi)}{M^3_{\phi^0}} \end{aligned}$$

where

$$z_{max} \equiv \frac{x}{x+1}$$

and

$$\Omega(z) \equiv z(1+\xi_1\xi_2)\left(\frac{1}{L_{ee}}\frac{dL_{\gamma\gamma}}{dz}\right) \quad .$$

We see that in order to maximize N_{ϕ^0} we must maximize both L_{ee} and $\Omega(z_\phi)$. How large, in principle, can we make $\Omega(z_\phi)$?

The function $\Omega(z)$ is characterized by five variables: the polarizations of the two electron beams, the polarizations of the two photon beams, and x. Figure 3 shows $\Omega(z)$ for two different values of x, and for various electron polarizations. Again, we assume that the laser beams have 100% circular polarization, and that the helicities of the laser and electron beams have opposite signs. For Figure 3 we make the additional assumption that the helicities of the two laser beams are equal to each other; this ensures that $\xi_1\xi_2 \approx 1$ for large z .

From Figure 3 we see that, for fixed x, the maximum value of $\Omega(z)$ increases as the electron polarization is increased. And, for fixed electron polarization, the maximum value of $\Omega(z)$ increases as x is increased. The growth of $\Omega(z)$ with x does not continue indefinitely, however.

At $x = 4.82$ the threshold for the reaction

$$\gamma_H\gamma_L \to e^+e^-$$

is crossed, where γ_H denotes a high energy photon and γ_L is a laser photon. The cross-section for $\gamma_H\gamma_L$ annihilation to an e^+e^- pair grows rapidly for $x >$ 4.82 and, consequently, the number of high energy photons escaping the conversion region drops precipitously. The maximum value for $\Omega(z_\phi)$ is therefore $\Omega(z_\phi)_{max} = 3.9$, and it occurs at $z_\phi = 0.8$ with $x = 4.82$, 100% laser photon polarization, 100% electron polarization, electron and laser beam helicities opposite to each other, and laser beam helicities equal to each other.

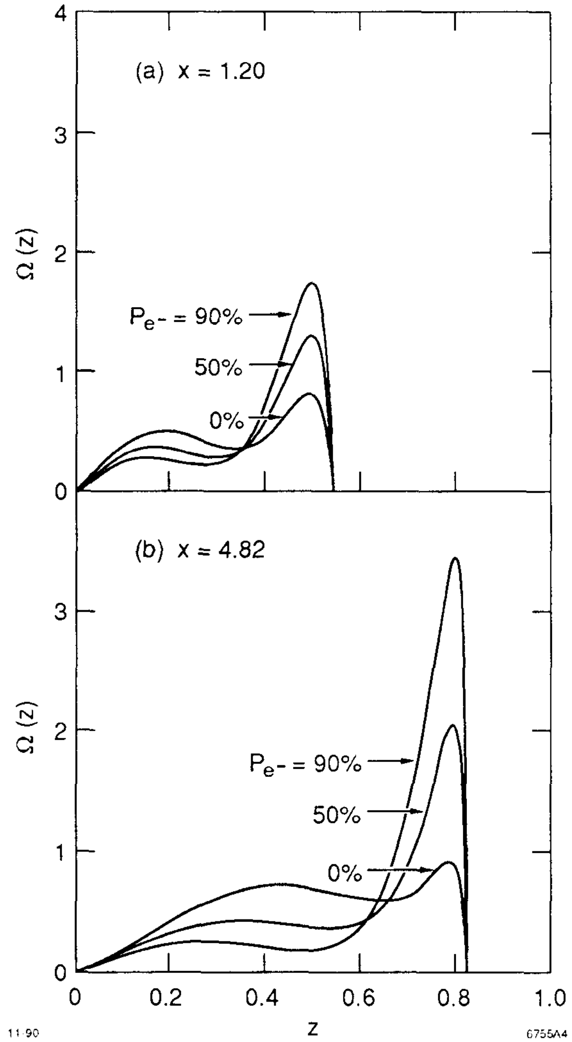

Fig. 3. Distributions for the function $\Omega(z)$ (defined in text) for (a) $x = 1.20$ and (b) $x = 4.82$. P_{e^-} denotes the electron beam polarization.

The background to Higgs boson production in $\gamma\gamma$ collisions comes from $\gamma\gamma$ annihilation to quark pairs, especially b quark pairs. The cross–section[15] for $\gamma\gamma \to f\bar{f}$, where f is a fermion, is given by

$$\frac{d\sigma(\gamma_1\gamma_2 \to f\bar{f})}{d\cos\theta} = \frac{4\pi\alpha^2 e_f^4 N_c\beta}{s(1-\beta^2\cos^2\theta)^2}\Big[1-\beta^4 - \left(\frac{1-\xi_1\xi_2}{2}\right)(1+\beta^2\cos^2\theta)(1-\beta^2(2-\cos^2\theta))\Big]$$

where α is the fine structure constant, e_f is the charge of the fermion in units of the electron charge, N_c is the number of colors, β is the velocity of the fermion, and

θ is the polar angle of the fermion.

The most interesting feature of the differential cross-section for $\gamma\gamma \to f\bar{f}$ is that it vanishes when $\beta = 1$ and $\xi_1\xi_2 = 1$. This is very encouraging, because $\beta \approx 1$ for b quarks at the beam energies we are considering, and $\xi_1\xi_2 \approx 1$ at $z = z_\phi$ for the electron and laser beam polarizations which maximize N_{ϕ^0}.

We have used a Monte Carlo program to simulate the production and detection of $b\bar{b}$ events at a $\gamma\gamma$ collider. The longitudinal boost of the $b\bar{b}$ system from asymmetric photon energies and the $b\bar{b}$ invariant mass spectrum are simulated fully. In order to fragment the b quarks we interface our Monte Carlo program to the Lund 6.3 parton shower Monte Carlo program with Lund symmetric fragmentation.

The detector simulation assumes the charged particle momentum resolution and electromagnetic energy resolution of the SLD detector:

$$\frac{\delta p}{p^2} = 0.001(\mathrm{GeV/c})^{-1}, \quad \frac{\delta E}{E} = \frac{0.08\mathrm{GeV}^{1/2}}{\sqrt{E}} \quad .$$

A Monte Carlo simulation is not used for b quark tagging; instead we simply assume a 50% event tagging efficiency for $b\bar{b}$ events and a 0% event tagging efficiency for $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ events.

Cuts are applied to the polar angle of the thrust axis (θ_t) and to the event acollinearity angle (ζ). The polar angle of the thrust axis must satisfy $|\cos\theta_t| < 0.8$. The event acollinearity angle is defined as follows. Let $\vec{p}_1$ and $\vec{p}_2$ be the vector sums of the momenta of the charged and neutral tracks in event hemispheres 1 and 2 respectively, where the event hemispheres are defined by the plane perpendicular to the thrust axis. ζ is defined to be 180° minus the angle made by the vectors $\vec{p}_1$ and $\vec{p}_2$. If an event hemisphere does not contain any tracks then ζ is assigned the value of 180°. We require that $\zeta < 7°$.

Figure 4 shows the results of our simulation. The dashed histogram is the observed mass distribution for $\gamma\gamma \to b\bar{b}$ only, while the solid histogram is the distribution for the combination of $\gamma\gamma \to b\bar{b}$ and $\gamma\gamma \to \phi^0 \to b\bar{b}$. The mass of the ϕ^0 is 90 GeV. The electron beam energy is $E_b = 57.0$ GeV and the laser photon energy is $\omega_0 = 5.5$ eV, so that $z_\phi = 0.8$ and $x = 4.82$. The laser beam helicity and the sign of the electron beam helicity are chosen to maximize N_{ϕ^0} as described above. The integrated luminosity is 5 fb^{-1}.

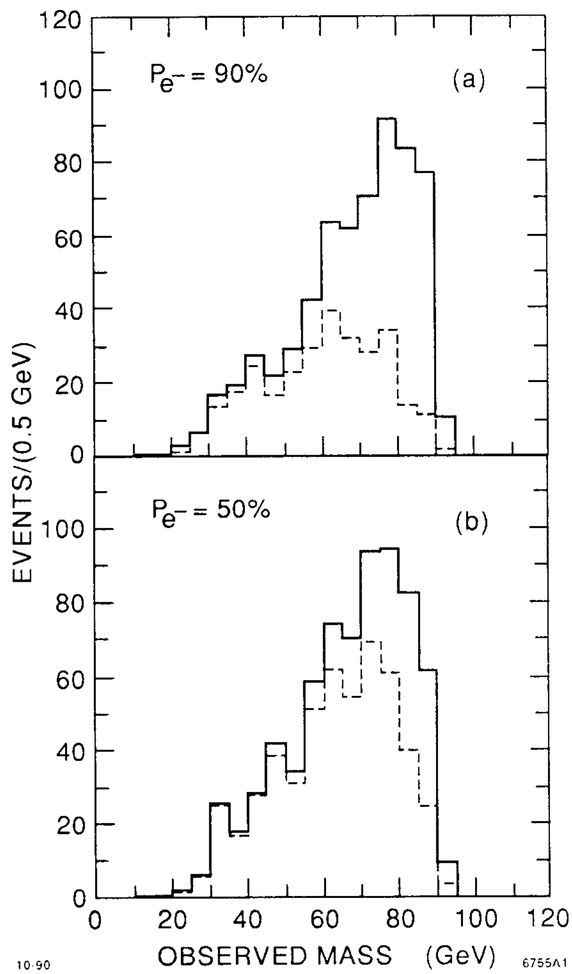

Fig. 4. Observed mass distributions for the process $\gamma\gamma \to b\bar{b}$ for (a) 90% e^- polarization and (b) 50% e^- polarization. The dashed histogram is continuum production only. The solid line is the sum of continuum and 90 GeV Higgs resonance production.

For 90% electron polarization the Higgs signal is substantial. At observed masses greater than 70 GeV there are 240 signal events and 90 background events. For 50% electron polarization the Higgs signal is smaller and the background is larger: 140 Higgs events and 200 background events for observed masses greater than 70 GeV. The reduction in the Higgs signal and the increase in the background are due to the fact that the product of the helicities of the high energy photons, $\xi_1\xi_2$, is dropping rapidly at $z = z_\phi = 0.8$ as the electron polarization is reduced. The drop in $\xi_1\xi_2$ at $z = 0.8$ is unfortunate in view of the fact that $\xi_1\xi_2$ remains fixed, irrespective of the electron polarization, at $\xi_1\xi_2 = 1$ for $z = z_{max} = .828$.

It should be possible to improve the Higgs boson signal–to–noise ratio beyond what is shown in Figure 4 by fitting for the $\gamma\gamma \rightarrow b\bar{b}$ cross-section at various values of z. The input to such a fit would be the observed mass distribution, the observed mass resolution function, and the differential $\gamma\gamma$ luminosity spectrum,

$$\frac{1}{L_{ee}}\frac{dL_{\gamma\gamma}}{dz} \quad .$$

The differential $\gamma\gamma$ luminosity spectrum would be measured using electron pairs, muon pairs, and light quark pairs produced in $\gamma\gamma$ annihilation.

C. The Higgs Bosons of Supersymmetric Theories

There are five Higgs bosons[24] in the minimal supersymmetric extension to the Standard Model: two charged Higgs bosons H^+ and H^-, two CP-even neutral Higgs bosons h^0 and H^0, and one CP-odd neutral Higgs boson A^0. The h^0 is the Higgs boson with a tree-level mass less than the Z mass, and a radiatively corrected mass of less than 130 GeV or so. Its properties are similar to the minimal Standard Model Higgs boson ϕ^0, so that the techniques developed for detecting the ϕ^0 will work for the h^0.

The H^0 and the A^0 are not at all like the ϕ^0. The A^0 does not couple to W^+W^- or ZZ at tree-level, and the tree-level coupling of the H^0 to W^+W^- and ZZ is suppressed. It therefore will be difficult, if not impossible, for the SSC to detect the H^0 and A^0, no matter what their mass. Ref. 18 shows how a 1 TeV NLC can successfully detect the Higgs bosons H^0 and A^0 through the process $e^+e^- \rightarrow H^0A^0$. It remains a topic of future study to determine the range of H^0 and A^0 masses accessible to a 500 GeV NLC.

The $\gamma\gamma$ partial widths for the h^0, H^0, and A^0 are just as interesting as the $\gamma\gamma$ partial width for the ϕ^0. J. Gunion and H. Haber[21] have calculated the $\gamma\gamma$ partial widths for h^0, H^0, and A^0. They have also estimated the signal-to-background for the production of these Higgs bosons through $\gamma\gamma$ annihilation, where the γ's are produced with the backscattered laser technique. Gunion and Haber conclude that it should be feasible to measure the $\gamma\gamma$ partial width over a wide range of h^0, H^0, and A^0 masses.

Just as LEP is able to set limits on charged Higgs bosons with masses as large as 90% of the beam energy, the NLC should be able to set limits on charged Higgs bosons with masses up to 220 GeV or so. Ref. 18 contains a study of how to isolate charged Higgs bosons at an e^+e^- collider with $\sqrt{s} = 1$ TeV.

V. DIRECT AND INDIRECT SEARCHES FOR NEW PARTICLES AND NEW PHENOMENA

A. Supersymmetric Particles

Regarding supersymmetry, the question we hope to answer with the next generation of colliders is whether or not supersymmetry is responsible for the electroweak energy scale. Searches for the Higgs bosons predicted by supersymmetric theories will be one part of this investigation. Direct searches for the supersymmetric partners of the known particles are also important, however.

Searches for gluinos and squarks will, for the most part, continue to be the domain of hadron colliders such as the Tevatron and SSC. However, as has been the case in the past[25], experiments at e^+e^- colliders will be able to set limits on squarks with less restrictive assumptions.

Neutralinos $\tilde{\chi}_i^0$ and charginos $\tilde{\chi}_i^+$ are best searched for at e^+e^- colliders. The NLC will be able to exclude charginos with masses up to 250 GeV. The NLC will also be able to exclude combinations of neutralinos, $\tilde{\chi}_i^0\tilde{\chi}_j^0$, where the masses of the neutralinos $\tilde{\chi}_i^0$ and $\tilde{\chi}_j^0$ sum to less than 500 GeV, and where both the $\tilde{\chi}_i^0$ and $\tilde{\chi}_j^0$ have some neutral Higgsino component.

Sleptons can only be searched for at the NLC. Again, the NLC should be able to set limits of 250 GeV on charged sleptons, and also on sneutrinos, as long as the sneutrinos are unstable and decay to visible objects.

The masses of neutralinos and charginos are more constrained in supersymmetric models than the masses of sleptons and squarks. In particular, the masses of the lightest neutralinos and charginos cannot be more than a few hundred GeV if the mass scale of supersymmetry is approximately 1 TeV[14]. Consequently, serious doubt will be cast on supersymmetry as an explanation for the electroweak energy scale if the NLC fails to find charginos or neutralinos.

If, on the other hand, supersymmetry is discovered, then the NLC will play a pivotal role in exploring the spectroscopy of supersymmetric particles. Here the many advantages of an e^+e^- collider — beam energy constraints, polarized beams, low background — will come into play in disentangling a complex spectrum of supersymmetric particles.

B. New Generations of Fermions

It may seem strange to talk about searches for new generations of fermions in light of recent results from SLC and LEP. However, following the limits from SLC and LEP on stable and unstable neutrinos, there remains the possibility that new generations of fermions exist whose neutrinos have masses greater than half the Z mass.

The fermion mass range which will be explored by the NLC is especially interesting because grand unified theories place upper bounds[26] of about 250 GeV on new fermion masses. These upper bounds come from studies of the renormalization of the fermion-Higgs Yukawa coupling constant λ_f. The assumptions which were used for the 200 GeV Higgs mass upper bound are also used for the 250 GeV fermion mass upper bound: no new physics between the electroweak scale and the grand unification scale, and the electroweak and strong interactions must remain perturbative up to the grand unification scale.

The NLC will be able to detect or exclude charged leptons, quarks, and unstable neutral leptons if the masses of these fermions are less than 250 GeV. Unfortunately, the NLC will not be sensitive to a new *stable* neutral lepton L^0. In particular, the process $e^+e^- \rightarrow \gamma L^0 \bar{L}^0$ cannot be used to detect an L^0 because the background from $e^+e^- \rightarrow \nu_e \bar{\nu}_e \gamma$ is too large.

C. Z′ Bosons

Presently, the lower bounds on Z' boson masses from CDF are in the neighborhood of 300 GeV, depending on the Z' model. These limits should improve by about 100 GeV in the next few years, so that it is unlikely that the NLC will be able to extend Z' boson mass limits by directly searching for Z' bosons. However, just as PEP and PETRA were sensitive to the Z boson, the NLC will be sensitive to Z' bosons with masses far greater than $\sqrt{s}$ through the effects of the Z' bosons on fermion pair cross-sections, forward-backward asymmetries, and polarization asymmetries.

J. Hewett and T. Rizzo have surveyed[27] the Z' mass limits obtainable with $5 fb^{-1}$ luminosity at the NLC for a variety of different models. They find that, depending on the model, Z' mass limits as high as 3 TeV can be achieved.

If a Z' boson exists, then the NLC can be used to explore its properties. The polarization asymmetries for different fermions can be used to identify the gauge group structure associated with the new Z'.

D. Technicolor Resonances

Ordinarily, technicolor physics is considered the province of colliders with constituent $\sqrt{s}$ values much larger than 1 TeV. And, indeed, the SSC should have no difficulty detecting a techni–ρ with mass a of 1.8 TeV, for example. We wish to point out, however, that the NLC at $\sqrt{s} = 500$ GeV may also be sensitive to a 1.8 TeV techni-ρ, and may have an advantage over the SSC in being sensitive to a 1.8 TeV techni-ω.

Techni–resonances are expected to be very broad. A 1.8 TeV techni-ρ for example should have a width of many hundreds of GeV. Figure 5 shows the influence of a 1.8 TeV techni-ρ on the cross-section for $e^+e^- \rightarrow W^+W^-$[28].

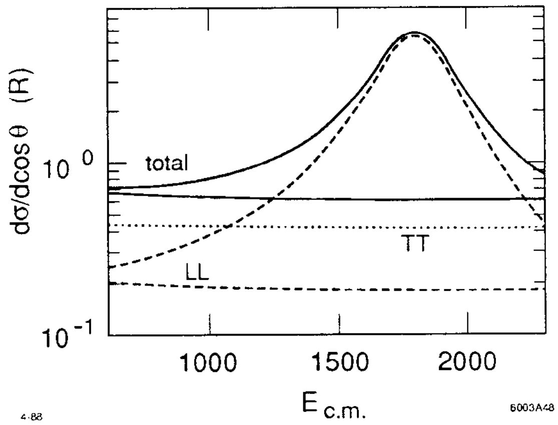

Fig. 5. The cross–section for $e^+e^- \rightarrow W^+W^-$ with and without a 1.8 TeV techni-ρ resonance. The dashed lines are the cross–sections for longitudinal W pairs, while the dotted line is the cross–section for transverse W pairs.

Note that there is a 25% enhancement in the cross-section for $e^+e^- \rightarrow W_L^+W_L^-$ from the 1.8 TeV techni-ρ at $\sqrt{s} = 500$ GeV, where W_L^+ denotes a longitudinally polarized W boson. If longitudinal W bosons can be successfully isolated in the final state, then the NLC should be sensitive to multi-TeV techni-ρ's.

A possible source of anomalous production of three gauge bosons is a 1 to 2 TeV techni–ω resonance. In analogy with the decay of the ω meson to three pions, the techni–ω would decay preferentially to three technipions , which would appear to us as three longitudinally polarized gauge bosons. The tail of a 1.8 TeV techni–ω resonance might be visible at the NLC, especially if the longitudinally polarized W's and Z's in the WWZ final state can be isolated.

E. Compositeness

The Bhabha scattering cross-section is remarkably sensitive to electron compositeness. Operating at $\sqrt{s} \approx 0.03$ TeV, PEP and PETRA experiments have set limits on the electron compositeness scale, Λ, of

$\Lambda > 2$ TeV. The NLC should continue this tradition; with the added power of polarized electron beams, the NLC should be able to set limits of 30 TeV or more on Λ.

VI. THE PHYSICS WITH THE CENTER-OF-MASS ENERGY UPGRADED TO 1.5 TEV

Most of the preliminary designs for 500 GeV e^+e^- colliders include schemes for upgrading the center-of-mass energy. A typical specification for the maximum center-of-mass energy is 1.5 TeV and the typical maximum luminosity at this energy is several $10^{34} cm^{-2} s^{-1}$. What extra physics would be gained if an e^+e^- collider ran for several years at 1.5 TeV center-of-mass energy, accumulating 100 to $500 fb^{-1}$?

Clearly, the mass reach for pair–produced particles would be extended from 250 to 750 GeV. Studies of Higgs boson detection[18] at e^+e^- colliders with $\sqrt{s} = 1$ TeV indicate that a minimal Standard Model Higgs boson with a mass as high as 1 TeV could be detected at $\sqrt{s} = 1.5$ TeV. The mass limits from indirect searches would also be improved. The Z' mass reach would be extended to about 10 TeV, and limits on the electron compositeness scale could reach 100 TeV.

Perhaps the most important reason for going to $\sqrt{s} = 1.5$ TeV, however, will be to study gauge boson scattering. If there are no Higgs bosons with masses less than 1 TeV, then gauge boson scattering will be the only way to explore the phenomena responsible for SU(2)$\times$U(1) symmetry breaking.

We will want to study the scattering of longitudinally polarized gauge bosons since they are the polarization states created by spontaneous symmetry breaking. Unfortunately, reactions such as $W_L^+W_L^- \to W_L^+W_L^-$ take place against a large background of uninteresting processes such as $W_T^+W_T^- \to W_T^+W_T^-$, where W_T^+ denotes a transversely polarized W; this is a very difficult experimental problem, and it is common to the SSC and the NLC.

There are several ways to study gauge boson scattering at an e^+e^- collider. In one method, the initial state e^+ and e^- each radiate a quasi-real gauge boson and the gauge bosons then interact. e^-e^- collisions can also be used for this purpose. This type of gauge boson scattering is sensitive to the $J = 0$ partial wave of W_LW_L scattering. Although some results can be achieved with an e^+e^- collider at $\sqrt{s} = 1.5$ TeV, studies indicate[29] that this method is most effective at center-of-mass energies of 2 TeV or more.

An alternate method, one which is perhaps more appropriate for $\sqrt{s} = 1.5$ TeV, is to observe the effects of final state rescattering in the processes $e^+e^- \to W_L^+W_L^-$[28] and $\gamma\gamma \to Z_LZ_L$[30]. We have already seen an example of the effects of final state rescattering in Figure 5. The process $e^+e^- \to W_L^+W_L^-$ will give us information about the $J = 1$ partial wave of gauge boson scattering while the process $\gamma\gamma \to Z_LZ_L$ will give us information about the $J = 0$ partial wave.

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