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Physics at High Energy Photon Photon Colliders [1]

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Abstract

I review the physics prospects for high energy photon photon colliders, emphasizing results presented at the LBL Gamma Gamma Collider Workshop. Advantages and difficulties are reported for studies of QCD, the electroweak gauge sector, supersymmetry, and electroweak symmetry breaking.

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Introduction

This report is a brief overview of research that could be performed at a high energy $\gamma\gamma$ collider. It is based primarily but not exclusively on 15 talks presented in the three theoretical physics parallel sessions at the LBL Gamma Gamma Collider Workshop. Written versions of these talks are (or should be) included in these proceedings, as are two excellent survey talks presented at the workshop by Brodsky[1] and Ginzburg[2].

The ability to obtain $\gamma\gamma$ and $e\gamma$ collisions by back-scattering low energy laser photons from high energy $e^{\pm}$ beams[3] can significantly enhance the physics program of a linear electron positron collider. With $\gamma\gamma$ collision energy of $\simeq$ 80% of the parent e^+e^- collider and comparable luminosity, a PLC (photon linear collider) would provide unique capabilities in addition to some welcome redundancy. Measurement of the two photon decay width of the Higgs boson would alone be sufficient motivation to add the $\gamma\gamma$ collision option to an e^+e^- collider.

Since the workshop is an ecumenical gathering of accelerator and laser physicists as well as experimental and theoretical particle physicists, I will preface this report with a few remarks on the current status of high energy physics, to establish the context within which a $\gamma\gamma$ collider must be viewed. The starting point is the standard model, which offers a compact and remarkably successful description of all extent experimental data. But the standard model is far from being a complete description of nature. To list just a few of the open questions, the standard model

- contains 17 arbitrary, unexplained parameters,
- unifies the weak and electromagnetic forces, but leaves unresolved the possibility of the further unification of the strong and gravitational forces,
- offers little insight into its own gross architectural structure — such as the $SU(3) \times SU(2) \times U(1)$ gauge symmetry and the number of quark-lepton families,
- provides a framework (the Higgs mechanism) for mass generation that implies a new force and associated quanta but leaves their precise properties unknown...

With one exception we are not sure if, how, or when we will find the answers to these questions nor to others I have not mentioned. The single exception, the problem of mass generation, necessarily has a very strong claim on our attention. The standard model *predicts* the existence of a fifth force and associated quanta that give mass to the quarks, leptons, and massive gauge bosons (W and Z). To account for the masses of the W and Z bosons, the new force must begin to emerge at an energy scale no greater than about 2 TeV.[4] This is a landmark in what is otherwise an unmarked wilderness. (The next unequivocal landmark is the Planck mass, at 10^{19} GeV, a scale not likely to fall within the purview of accelerator physics for the next few millenia.)

The prediction of a fifth force follows from the Higgs mechanism, which is an essential feature of the standard model. Like any prediction in science, this prediction could fail. If it fails the standard model fails. But the TeV scale landmark still stands, since we would then discover a deeper theory that has masqueraded until now as the standard model. The effects of the new theory would begin to emerge in the same energy region in which the fifth force must emerge if the standard model is correct.

We are all going to be very surprised if the Higgs mechanism fails to explain the W and Z boson masses. But outside particle physics it is not widely understood that the Higgs *mechanism* does not necessarily imply the existence of Higgs *bosons*. There are actually two possibilities:[4]

1. The fifth force is weak in which case there are Higgs bosons below 1 TeV and perturbation theory can be applied to Higgs sector interactions.

2. The fifth force is strong in which case we do not expect Higgs bosons but a more complex spectrum of strongly interacting quanta, probably beginning between 1 and 3 TeV, and perturbation theory is inapplicable. The unequivocal signal for this case is the existence of strong WW scattering above 1 TeV.

There is a prejudice among many theorists in favor of supersymmetry, which would imply a weak fifth force and at least one light Higgs boson, with mass $\lesssim$ 140 GeV. But the evidence is far from definitive and we should prepare for either possibility.

The LHC operating at its 14 TeV design energy and its $10^{34}\mathrm{cm}^{-2}$ sec^{-1} design luminosity will probably be able to determine the strength of the fifth force whether weak or strong and to provide the first glimpses of the associated new quanta.[5, 6] To have the same capability an e^+e^- linear collider would need center of mass energy of at least $\sim$ 2 TeV and luminosity $\sim 10^{34}$ cm^{-2} sec^{-1},[7, 8, 9] which will not be possible until well after the expected start date of the LHC. But whatever is glimpsed at the LHC will not be understood without exhaustive further study, at which an e^+e^- linear collider should excel. To evaluate the physics potential of an $e^+e^-/e\gamma/\gamma\gamma$ linear collider complex, we focus on its analyzing power more than simply on its discovery potential. The LHC should tell us a great deal about the energy and luminosity a linear collider would need for detailed studies of the symmetry breaking sector. Today, in our ignorance, we must consider a range of possibilities.

In the following sections I will review the theoretical contributions to the workshop as well as some other relevant material. Topics include QCD, the electroweak gauge sector, supersymmetry, and electroweak symmetry breaking in both the weak and strong fifth force scenario. In view of the preceding remarks it will come as no surprise that nearly two thirds of the contributed talks concerned electroweak symmetry breaking.

QCD

In this section I will sketch two topics in QCD that could be studied advantageously at an $e^+e^-/e\gamma/\gamma\gamma$ collider complex: the photon structure functions and the top quark threshold region.

Photon Structure Functions

This is a subject that the $e\gamma$ collider *owns*. The inclusive scattering process

$$e + \gamma \rightarrow e/\nu + X ,$$

where X represents any hadronic final state, is mediated by exchange of a highly virtual γ, Z, or W, and probes the short distance hadronic structure of the photon, just as deep inelastic electron nucleon scattering probes internal nucleon structure. Deep inelastic scattering from a photon target has some unique properties: the structure function F_2 increases logarithmically with the four momentum Q^2 of the virtual exchanged gauge boson *and* is completely determined in the $Q \rightarrow \infty$ limit by perturbative analysis,[10] in which limit it dominates the cross section by virtue of the logarithmic enhancement. This contrasts with the nucleon structure functions, for which the scaling laws (and their QCD corrections) are predicted but the functional form cannot be determined perturbatively.

Because of the experimental difficulty of isolating the leading photon structure function, the predicted scaling law and functional form have not been definitively tested. A high energy $e\gamma$ collider would offer the best chances to carry out these fundamental measurements. I am not aware of feasibility studies for such a program. It is clearly worth studying.

At the workshop Frances Halzen presented a very nice talk outlining a method to extract the gluonic component of the photon structure function.[11] The gluonic component is not determined by perturbative analysis and is important for a variety of applications, including background estimates for $\gamma\gamma$ collisions and in cosmic ray physics. The idea is to measure the rapidity distribution for production of heavy quark pairs, $\bar{b}b$ or $\bar{c}c$. Halzen and collaborators Eboli and Gonzalez-Garcia observe that the signal in the extreme backward direction (the target fragmentation region) is overwhelmingly dominated by the gluonic component of the target photon structure function. Measurement of the

$\bar{b}b$ or $\bar{c}c$ cross sections in this region then provides a measurement of the gluonic component.

The observation is made plausible by the fact that it holds for a wide range of model structure functions. However its generality is not clear to me nor how it might be tested. Since the analysis was "fresh off the blackboard" at the time of the workshop, these issues may be addressed in the future.

Top quark threshold region

This subject was not studied at the workshop but since it is potentially very interesting I will briefly review it. There are tantalizing possibilities to study the $\bar{t}t$ threshold region at a $\gamma\gamma$ collider, though it remains to be seen how well they can actually be implemented.

For experimentally relevant masses, $m_t > 150$ GeV, the top quark lifetime is shorter than the characteristic time scale of strong interactions (i.e., $\Gamma_t > \Lambda_{QCD}$), so that the top quark decay $t \to bW$ occurs before toponium formation can occur. Therefore we do not expect narrow toponium resonances like the charmonium and bottomonium states that taught us so much about QCD. That was the bad news. The good news, heralded by Fadin and Khoze, is that the broad top quark decay width provides an infra-red cutoff so that the entire threshold region can be studied with perturbation theory.[12] The running coupling constant is evaluated at the scale

$$\alpha_S = \alpha_S(m_t\sqrt{\Gamma_t^2 + E^2})$$

where $E = \sqrt{s} - 2m_t$, and therefore never becomes nonperturbatively large.

There are then some interesting possibilities:

- The shape and position of the $\gamma\gamma \to \bar{t}t$ threshold enhancement determine m_t and α_S, though the beam energy spread dilutes the quality of the measurement.[13, 14]
- With $\geq 95\%$ polarized photon beams of opposite helicity, $\lambda_1\lambda_2 = -1$, which suppresses the dominant s-wave, production of $\bar{t}t$ in the p-wave could be observed,[14] with possible precise determinations of α_S and m_t. In e^+e^- collisions the s-wave cannot be similarly suppressed but it may still be possible to probe the p-wave by measuring its interference with the s-wave.[15]
- We could measure the important and inaccessible top quark decay width *if* we could obtain energy resolution $\Delta E_{\gamma\gamma} \lesssim 1$ GeV. For now this seems like asking for a perpetual motion machine, since the only known way to decrease the energy spread is by increasing the distance between the

conversion point and the interaction point, with a loss of luminosity proportional to the square of the energy spread.

- With linearly polarized photon beams we could measure t quark polarization induced by QCD final state interactions, providing a precise determination of α_S, and probe for interactions outside the standard model.[16, 17] These polarization effects are expected to survive the energy spread of the beams.

Time will tell how practicable these proposals are.

Electroweak Gauge Sector

Photon photon scattering is the process of choice for testing the interactions of the electroweak gauge sector, since we begin with two gauge bosons in the initial state. It is not surprising that it affords the most sensitive probes of gauge sector interactions for a given e^+e^- collider energy.

The dominant process is $\gamma\gamma \to WW$, which has a large, asymptotically constant cross section,

$$\sigma = \frac{8\pi\alpha^2}{M_W^2} \sim 93 \text{ pb},$$

corresponding to $\sim 10^6$ W^+W^- pairs per 10 fb^{-1}. Compared to the point-like photon mediated cross section $\sigma_{POINT}(e^+e^- \to \mu^+\mu^-)$, the traditional ratio R grows with energy,

$$R(\gamma\gamma \to WW) = \frac{\sigma(\gamma\gamma \to WW)}{\sigma_{POINT}} = \frac{6s}{M_W^2}$$

where s is the square of the total center of mass energy. Other $2 \to 2$ processes in $\gamma\gamma$ scattering and e^+e^- annihilation have cross sections that fall like s^{-1} (up to logarithms in some cases). At $\sqrt{s} = 500$ GeV we have $R(\gamma\gamma \to WW) \sim 230$, an order of magnitude larger than $R(e^+e^- \to WW) \sim 18$ at the same energy.

This is another instance of the particle physics maxim "yesterday's Nobel prize, tomorrow's background." The large WW cross section is advantageous in testing for anomalous gauge sector interactions but is a decided disadvantage in many searches for new physics for which it provides an enormous background. This will be evident in the discussions of Higgs sector and supersymmetry signals in the next sections.

The WW cross section is not as overwhelming as the above equations seem to suggest. The constant total cross section arises from singularities in the forward and backward directions, and as the energy increases the scattering becomes more and more concentrated at small scattering angles. The cross section for scattering greater than a fixed angle $\theta > \theta_0$ has the conventional scaling behavior, falling like s^{-1}. Integrating over all angles we have schematically

$$\sigma \sim \int dt \frac{1}{(t - M_W^2)^2} \sim \frac{1}{M_W^2}$$

whereas at large s with $\theta > \theta_0$

$$\sigma \sim \int_{\theta > \theta_0} dt \frac{1}{(t - M_W^2)^2} \sim \frac{1}{s} \frac{1}{(1 - \cos\theta_0)}.$$

The effect of the scattering angle cut is shown in table 1 for $\gamma\gamma$ collisions at 0.5, 1.0, and 2.0 TeV. Though it reduces the cross section tremendously, especially at the highest energies, the surviving cross sections are still very big relative to typical signal cross sections of interest. In practice it is not possible to cut on the center of mass scattering angle because of the energy spread of the photon beams. In a study of supersymmetry signals described in the next section, Murayama and Kilgore[18] find that it is more effective to cut on the transverse momentum of the W or its decay products than on the laboratory scattering angle.

Following the principle "when you've got lemons make lemonade," it is worth considering whether a PLC could be used as a W factory. Is there an interesting physics program in high statistics studies of W boson decays? To stimulate consideration of the question and to provide guidance toward a constructive answer, I announced the Second Chanowitz Prize[9] at the Second KEK Topical Conference on e^+e^- Collisions: lunch with Michael Peskin for suggesting an interesting W factory program (Chez Panisse in Berkeley) or for proving a no-go theorem (SLAC cafeteria). As of this writing the prize is still unclaimed.

As shown first by Jikia[19] and confirmed analytically[20] and numerically[21], the large cross section for $\gamma\gamma \to WW$ engenders a surprisingly large cross section for $\gamma\gamma \to ZZ$ via the WW intermediate state. Measurement of $\sigma(\gamma\gamma \to ZZ)$ will be a significant test of the electroweak gauge sector at the quantum loop level. Though also sharply peaked in the forward direction, $\gamma\gamma \to ZZ$ is still a formidable background. Even after cuts on the scattering angle or transverse momentum, it overwhelms the Higgs boson signal for $m_H \gtrsim 400$ GeV and obscures the growing contribution to the cross section from ultraheavy charged quanta[22].

More recently Jikia and collaborators have computed the cross sections for $\gamma\gamma \to \gamma Z$ [23] and $\gamma\gamma \to \gamma\gamma$,[24] which are also dominated by the W loop contribution. It is splendid to imagine measuring the elastic, on-shell scattering of light by light! With a PLC at a 500 GeV e^+e^- collider, there would be ~ 50 events with scattering angle $|\theta| > 30°$ per 10 fb^{-1} of $\gamma\gamma$ luminosity.

Given the two gauge boson initial state, a $\gamma\gamma$ collider is clearly the premier facility for testing the electroweak gauge sector interactions of the standard model. The generic sensitivity of the three beam combinations at given e^+e^- collider energy is $\gamma\gamma > e\gamma > e^+e^-$. This ordering does not apply to every possible anomalous interaction. For instance, Eboli and Han presented studies of γZWW interactions for which $e\gamma$ collisions have the greatest sensitivity. Eboli and collaborators[25] assume an interaction invariant under $U(1)_{\rm EM}$, C, P, and $SU(2)_{\rm Custodial}$ but not under the complete local $SU(2)_{\rm L} \times U(1)_{\rm Y}$,

$$\frac{\pi\alpha}{4\Lambda^2} a_n W_\alpha \cdot W_\nu \times W_\mu^\alpha F^{\mu\nu} \ .$$

They find for $\Lambda = M_W$ that a 3σ constraint $-1.2 < a_n < 0.74$ can be achieved with 10 $\rm fb^{-1}$ at a 500 GeV e^+e^- collider.

Han and collaborators[26] considered a γZWW interaction that is locally $SU(2)_{\rm L} \times U(1)_{\rm Y}$ and CP invariant but violates C, P, and $SU(2)_{\rm Custodial}$,

$$\hat{\alpha}\left(\frac{2e^4}{\cos\theta_W \sin^3\theta_W}\right)\frac{v^2}{\Lambda^2}\epsilon^{\alpha\beta\mu\nu} W_\alpha^- W_\beta^+ Z_\mu A_\nu \ .$$

With 10 $\rm fb^{-1}$ at parent e^+e^- colliders of 0.5 and 2.0 TeV they find 3 σ limits of $\hat{\alpha} \lesssim 12$ and $\hat{\alpha} \lesssim 1$ respectively for $\Lambda = 2$ TeV. The results are very sensitive to the scattering energy, much less sensitive to the luminosity.

In some cases enhanced sensitivity can be achieved by combining data from all three beam combinations of an $e^+e^-/e\gamma/\gamma\gamma$ collider. This was nicely illustrated by Choi and Schrempp[27], who showed that the constraint on the anomalous magnetic moment of the W obtained at a 500 GeV collider is vastly improved by combining measurements from all three collision options.

Supersymmetry

Murayama presented the results of a study prepared for the workshop in collaboration with Kilgore, to compare the scalar muon signal at a $\gamma\gamma$ collider with the signal at an e^+e^- collider.[18] The emphasis is not simply on discovery potential but on the ability to make a precise measurement of the mass. If supersymmetry is discovered such measurements will be extremely important since they would then test theories at much higher energy scales, such as supergravity, for which the natural scale is only a few orders of magnitude below the Planck mass. The scalar muon is also a prototype for many other measurements and searches that use lepton and missing energy signals and are therefore vulnerable to a large WW background.

The signal is $\gamma\gamma \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^- +$ LSP $\overline{\rm LSP}$ where LSP refers to the lightest supersymmetric particle, which escapes from the detector like a neutrino.

A dangerous background is then $\gamma\gamma \to W^+W^- \to \mu^+\mu^- + \bar{\nu}\nu$. The signal is enhanced by a factor ~ 2 relative to the background by choosing photon beams of equal helicity so that $J_Z = 0$, but before additional cuts the surviving background is still at least 10 times larger than the signal. Assuming a 150 GeV smuon with $m_{LSP} = 100$ GeV and a 500 GeV e^+e^- collider, Murayama and Kilgore eliminate the background by an acoplanarity cut and a cut on the muon transverse momentum. The surviving, essentially pure signal has a 20 fb cross section, so 10 fb^{-1} is more than adequate for discovery.

It is necessary to cut hard enough to obtain an essentially pure signal sample in order to make an accurate measurement of the smuon mass. With 50 fb^{-1} a 5 GeV measurement of the mass is possible.[18] While impressive this does not match the 1 GeV accuracy that can be obtained from 500 GeV e^+e^- collisions with 20 fb^{-1} using right hand polarized electrons to remove the WW background.[28] The increased accuracy is due in part to the smaller energy spread of the e^+e^- beams. Increasing ρ (the distance from the $e\gamma_{\rm Laser}$ conversion point to the $\gamma\gamma$ interaction point) decreases the $\gamma\gamma$ energy spread but at too great a cost in luminosity.

This study indicates the generic difficulty of using $\gamma\gamma$ collisions for such measurements, due to the large WW background and the large spread in photon energies. At higher energy colliders beamstrahlung also spreads the the e^+e^- center of mass energy, reducing the relative advantage of e^+e^- collisions.

As mentioned by Murayama, a $\gamma\gamma$ collider has a great advantage over its parent e^+e^- collider for the study of heavy scalar superpartners such as the top squark or stop, $\tilde{t}$. In e^+e^- collisions stop-antistop would be produced in the kinematically suppressed p-wave and could not be effectively studied unless the available collider energy were much greater than the threshold production energy. In $\gamma\gamma$ collisions stop-antistop pairs are produced in the s-wave, which can be further enhanced by choosing photon beams of equal helicity.

Electroweak Symmetry Breaking

Though more careful studies are needed to be sure, it is likely that the LHC at design energy and luminosity can provide observable signals of the strong WW scattering that occurs at $\sqrt{s_{WW}} > 1$ TeV if the symmetry breaking fifth force is strong.[5, 6] Those measurements determine the energy scale of the fifth force and associated quanta whether they detect a signal or not, since the absence of strong scattering signal would imply a weak fifth force and Higgs bosons below $\simeq 1$ TeV. Higgs bosons themselves would also be observable at the LHC, though with difficulty in the "intermediate mass region" below the ZZ threshold and above the ~ 80 GeV reach of LEP II. The supersymmetric Higgs bosons are more difficult to observe at LHC than the Weinberg-Salam

Higgs boson, but supersymmetry itself is likely to be easily discovered since the strongly interacting superparticles (squarks and gluinos) would be produced with sizeable cross sections.

Higgs bosons are readily observable at e^+e^- colliders given sufficient energy and luminosity. To cover the mass range from the current 60 GeV limit to the likely upper limit of $\sim$ 1 TeV, we would need a collider with total energy $\sqrt{s} \geq \mathrm{MIN}(m_H + m_Z,\ m_H/0.7)$ and integrated luminosity ranging from 1 fb^{-1} at the low end to $\simeq$ 200 fb^{-1} at the upper end.[7, 8, 9] The Higgs bosons of supersymmetric theories are more readily observable at e^+e^- colliders than at hadron colliders.

The question then is "What does a $\gamma\gamma$ collider bring to the party?" There are, at least, the following answers:

- ability to measure $\Gamma(H \to \gamma\gamma)$ for $m_H \lesssim 350$ GeV — a fundamental measurement as described below,
- extending the reach of an e^+e^- collider for the most elusive supersymmetric Higgs bosons, the heavy scalar H^0 and the pseudoscalar A^0,[29]
- complementary observations of the charged Higgs bosons $H^\pm$ of nonminimal Higgs sectors[30],
- circular and linear polarization of the photon beams offer unique analyzing power,e.g., to measure the parity of the Higgs bosons[31, 32] and to enhance signals relative to backgrounds,
- ability to observe strong WW scattering in $\gamma\gamma \to WWWW, WWZZ$[33, 34, 35] and to observe strong WW resonances in $\gamma\gamma \to ZZ$,[36, 37] though in colliders of the far future with $\sqrt{s} \gtrsim 2$ TeV.

These topics are reviewed below.

Higgs Bosons

A $\gamma\gamma$ collider is the facility of choice to measure the $\gamma\gamma$ decay width of the Higgs boson. This is not just an important test of the Higgs theory but also probes the existence of arbitrarily heavy quanta that may be far too heavy to produce in existing or even presently contemplated accelerators.[38] The $H \to \gamma\gamma$ decay proceeds via all intermediate quanta that are electrically charged and receive mass from the Higgs boson. All such quanta of spin 0 or 1/2 that are heavier than m_H contribute depending only on their spin and electric charge but *independently of how heavy they may be.* Consequently $\Gamma(H \to \gamma\gamma)$ is an amazing window to the highest mass scales that are coupled to the Higgs sector.

Several presentations at the workshop considered the question of how to detect a Higgs boson with mass below the ZZ threshold, which would decay predominantly to $\bar{b}b$. The problem is how to see the signal over $\bar{b}b$ backgrounds from "direct" $\gamma\gamma \to \bar{b}b$ production and from $\bar{b}b$ production by "resolved" photons[39] which are produced predominantly by scattering from the gluon component of the photon. The resolved photon background is large but soft and can be controlled by choosing the e^+e^- energy so that the Higgs signal occurs at the maximum $\gamma\gamma$ energy,[29] $m_H \sim E_{\gamma\gamma}^{MAX} \sim 0.8E_{e^+e^-}$. Essentially no $\bar{b}b$ pairs from resolved photons occur at the upper edge of phase space, since they are produced in association with other internal quanta of the photon.

The leading order direct background is controlled by choosing equal helicity photon polarizations so that $J_Z = 0$, in which case $\gamma\gamma \to \bar{b}b$ is suppressed by a factor m_b^2/s in the cross section.[29, 40] (The suppression follows from the chiral invariance of QCD interactions which forbids creation of a massless fermion-antifermion pair with $J_Z = 0$.) As discussed by Borden and Jikia in presentations at the workshop[41, 42] the kinematical suppression does not apply to the leading QCD correction, $\gamma\gamma \to \bar{b}bg$, since after gluon radiation the $\bar{b}b$ system need not be in a $J = 0$ state. Unless it can be controlled the surviving background would overwhelm the signal. While differing in some respects, both studies concluded that the background can be controlled with additional cuts. Borden estimated that a 10% measurement of the decay width could be accomplished with $10 - 20$ fb^{-1}. A critical requirement is $90 - 95\%$ rejection capability for $\bar{c}c$.

Above ZZ threshold $\gamma\gamma \to H \to ZZ$ must be distinguished from the huge WW background discussed in the previous section. This rules out the four jet final state, since even with perfect jet-jet mass resolution intrinsic smearing from the Z and W widths may submerge the ZZ signal in the tail of the WW background. It is probably necessary to tag at least one of the Z's, either in its electron or muon decay mode or perhaps in the neutrino mode, i.e., $ZZ \to l^+l^- + jj$ with $l = e, \mu$ (net branching ratio from $ZZ \sim 10\%$), or $ZZ \to \bar{\nu}\nu + jj$ (net branching ratio $\sim 40\%$). This works for $m_H \lesssim 350$ GeV, beyond which the signal begins to sink into the ZZ continuum background.[19, 20, 21] The width $\Gamma_{\gamma\gamma}$ can be measured to $\sim 10\%$ at the lower end of the ZZ mass range (more precisely, $\Gamma_{\gamma\gamma}B_{ZZ}$) but is of course poorly measured near the upper end as the signal disappears.[40]

In an e^+e^- collider the supersymmetric Higgs bosons H^0 and A^0 are produced in association, $e^+e^- \to HA$. While a two-for-one sale seems economical, the cost is the energy to reach the threshold $\sqrt{s_{e^+e^-}} > m_H + m_A$. The claimed reach at a 500 GeV collider is ~ 200 GeV in the individual Higgs boson masses. This can be extended using the $\gamma\gamma$ collider option where H and A can be produce individually. For moderate values of the mixing parameter $\tan\beta$, they can be detected decaying to $\bar{b}b$. The claimed reach for a parent e^+e^- collider of 500 GeV, using $\gamma\gamma \to h, H, A \to \bar{b}b$ is then to the theoretical maximum, ~ 145 GeV, for the light scalar h, the interval $110 < m_H < 200$ GeV for H, and $100 < m_A < 2m_t$ for A.[29] The latter significantly extends the reach relative to the e^+e^- collision mode.

Linear polarization would enable direct measurement of the Higgs bosons parities.[31, 32] The scalars h and H couple couple to the photon polarization vectors like $\epsilon_1 \cdot \epsilon_2$ while the pseudoscalar A couples like $\epsilon_1 \times \epsilon_2 \cdot k$ where k is the photon three-momentum in the center of mass. Kramer *et al.*[32] observe that linear polarization of 65% may be obtained by choosing a lower energy laser (requiring an increase of 1.7 in the e^+e^- energy to maintain a fixed $\gamma\gamma$ energy). It appears that 100 – 200 fb^{-1} may be needed to see the asymmetries above background.

The leading QCD corrections to $\Gamma(H \to \gamma\gamma)$ were reported by Najima at the workshop.[43, 44] The corrections are very small for $m_H < m_t$ but are large, of order 1, for $m_H \gg m_t$.

Strong WW scattering

Berger reported on a study,[36] carried out for the workshop, of strong interaction effects in $\gamma\gamma \to Z_L Z_L$, where the subscript L denotes longitudinal polarization. If electroweak symmetry breaking is due to a strong fifth force, it would be reflected in the $\gamma\gamma \to Z_L Z_L$ cross section, which would then be analogous to the hadronic process $\gamma\gamma \to \pi^0\pi^0$. This process has been explored by others,[37] though in most instances without detailed consideration of the very large ZZ background. Using methods developed in the study of strong WW scattering at hadron supercolliders, the study reported by Berger focused on whether the strong scattering signal would be visible above the large ZZ background. The conclusion is that nonresonant effects are probably not observable but that resonances, analogous to the hadronic tensor meson $f_2(1270)$, could be observed with 100 fb^{-1} and sufficient energy to produce the resonance. Such resonances are not likely to occur below ~ 2 TeV.

A more promising method to study nonresonant strong WW scattering was suggested by Brodsky[33] and has been studied at this workshop by Jikia[34] and Cheung.[35] In analogy to strong WW scattering at pp colliders[45], $qq \to qqW_L W_L$, Brodsky proposed considering $\gamma\gamma \to WWW_L W_L$ or $\gamma\gamma \to WWZ_L Z_L$. (The analogous process for H boson production, $\gamma\gamma \to WWH$, has been studied by Baillargeon and Boudjema.[46]) At the workshop Cheung[35] presented signals (without backgrounds) for a variety of strong scattering models, using the effective W approximation and the equivalence theorem. Jikia reported a complete leading order calculation of the backgrounds, $\gamma\gamma \to WWWW$

and $\gamma\gamma \rightarrow WWZZ$, requiring in the first case evaluation of 240 Feynman diagrams[34]. (Cheung has subsequently also evaluated the backgrounds.[47])

With the background evaluated Jikia estimated the energy and luminosity necessary to observe heavy Higgs bosons and strong WW scattering. With 200 fb^{-1} he finds that a $\gamma\gamma$ collider at a 1.5 TeV e^+e^- collider is needed to observe the standard model Higgs boson with $m_H = 700$ GeV, while a $\gamma\gamma$ collider at a 2 TeV e^+e^- collider is needed for $m_H = 1$ TeV. From these cases he concludes that the reach of a $\gamma\gamma$ collider based on a 2 TeV e^+e^- collider is similar to that of a 1.5 TeV e^+e^- collider operating in e^+e^- mode assuming equal $\gamma\gamma$ and e^+e^- luminosities, not surprising since $\sqrt{s_{\gamma\gamma}^{\text{MAX}}} \simeq 0.80\sqrt{s_{e^+e^-}}$. He incorporates the effect of experimental efficiencies by consulting the study of heavy Higgs boson production and strong WW scattering in e^+e^- collisions by Kurihara and Najima[7], who did include detector simulation; they found for 2 TeV e^+e^- collisions that ~ 300 fb^{-1} is needed to obtain a 3 σ strong WW scattering signal. Jikia then infers that a $\gamma\gamma$ collider at a 2 TeV e^+e^- collider (with $\sqrt{s_{\gamma\gamma}^{\text{MAX}}} \simeq 1.6$ TeV) could not observe strong WW scattering unless $\gamma\gamma$ luminosities much larger than $O(200)$ fb^{-1} are possible. Without attempting to incorporate detector simulation, Cheung[47] concludes more optimistically that strong scattering could be seen with ~ 100 fb^{-1} with a $\gamma\gamma$ collider at a 2 TeV e^+e^- collider, and that ~ 10 fb^{-1} could suffice at a 2.5 TeV e^+e^- collider.

Conclusion

The presentations at this workshop show that a photon linear collider would be a valuable adjunct to the e^+e^- linear collider on which it would be based. Relative to the parent e^+e^- collider, the $\gamma\gamma$ collider suffers from proportionately larger WW backgrounds and, especially in the NLC energy range, from broader beam energy spread. But it provides a variety of significant advantages, with unique access to some fundamental physics, using beams that can be customized for different physics goals.

By choosing the relative helicities of the lepton and laser-photon beams, "broad" or "narrow" band beams can be provided, with the narrow band beam offering much of its luminosity at the highest energies, typically $\sim 80\%$ of the parent e^+e^- collider energy. Increasing the distance between the conversion point and the interaction point improves the monochromaticity further, though at a cost in luminosity proportional to the square of the decrease in energy spread. Circular polarization is readily achieved and enhanced linear polarization is possible by lowering the energy of the laser photons.

There is a range of studies for which $\gamma\gamma$ and $e\gamma$ colliders would be uniquely suited. The $e\gamma$ collider mode is the facility of choice for probing the photon structure functions, a fundamental subject in QCD with important phenomenological implications. Valuable measurements of the $\bar{t}t$ threshold region may be possible in $\gamma\gamma$ collisions, especially with polarized beams. If supersymmetric particles exist at the electroweak scale, a $\gamma\gamma$ collider would be optimal for detailed study of heavy squark-antisquark states that are suppressed by p-wave phase space in e^+e^- collisions. Since all the initial energy is concentrated in two gauge bosons, $\gamma\gamma$ collisions offer the most sensitive probes of the electroweak gauge sector for given e^+e^- collider energy. For $m_H \lesssim 350$ GeV the $\gamma\gamma$ collider provides the best (and for $m_H > 2m_W$ probably the only) measurement of the two photon decay width of the Higgs boson. It can extend the reach of the parent e^+e^- collider for the pseudoscalar and heavy scalar Higgs bosons of supersymmetric models. In addition to its unique capabilities, a $\gamma\gamma$ collider would provide welcome redundancy with measurements from e^+e^- and proton-proton collisions.

Aided by my nearly perfect ignorance of accelerator physics and of linear colliders in particular, I can imagine another way in which high energy $\gamma\gamma$ colliders could be crucial. Though unlikely, it is possible that the ratio of luminosities $\mathcal{L}_{\gamma\gamma}/\mathcal{L}_{e^+e^-}$ might be large not just by virtue of an enhanced numerator, as discussed at this workshop, but also if the denominator is unexpectedly small. The issues that determine the luminosity of e^+e^- collisions are not identical with those that determine the $\gamma\gamma$ luminosity, and unanticipated difficulties might affect one but not the other. If for instance unexpected beam-beam instabilities were found to suppress TeV e^+e^- luminosities below the necessary 10^{33} to 10^{34} cm^{-2} sec^{-1} level, it might still be possible to obtain the necessary luminosities in $\gamma\gamma$ and $e\gamma$ collisions. The $\gamma\gamma$ collider would then be the only game in town, and its "redundant" access to many subjects I have not discussed would become crucial.

Though we are still at an early stage in our thinking — about both the accelerator and particle physics — it seems clear that an $e^+e^-/e\gamma/\gamma\gamma$ collider complex would be a very useful extension of a linear e^+e^- collider. Continued R&D is surely a prudent investment.

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Table 1: Cross section in picobarns for $\gamma\gamma \longrightarrow W^+W^-$ for various $\gamma\gamma$ center of mass energies and minimum scattering angles.

$\sqrt{s}$(TeV)	σ_{total}	$\cos\theta < 0.8$	$\cos\theta < 0.6$
0.5	77	9.7	3.1
1.0	88	2.9	0.86
2.0	91	0.78	0.22