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Symmetry breaking and electroweak physics at Photon Linear Colliders

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Abstract

The physics potential of a high-energy photon collider is reviewed. The emphasis is put on aspects related to the symmetry breaking sector, including Higgs searches and production of longitudinal vector bosons.

ENSLAPP-A-527/95
arch-ive/9508218
June 1995

§ URA 14-36 du CNRS, associée à l'E.N.S de Lyon et à l'Université de Savoie.

Talk presented at the Photon'95 Conference, Sheffield, England, April 8-15, 1995.

1 Introduction

The option of building a photon-photon interaction region at an e^+e^- linear collider is now taken seriously under consideration. Based on the idea of using laser-induced backscattered photons for inducing high-energy photon collisions, a $\gamma\gamma$ collider (PLC) gives rise to new physics opportunity[1]. The issues concerning electroweak physics will be summarized in this talk[2].

Since the symmetry-breaking mechanism remains the last open question in the standard model, an important part of the planning at any future collider must be devoted to that. This obviously includes searches for the Higgs particle and the determination of its properties. One unique opportunity for $\gamma\gamma$ colliders in that respect is the direct measurement of the $H\gamma\gamma$ coupling. Should the Higgs searches remain fruitless, the study of the longitudinal W sector would give a handle on the symmetry breaking mechanism. Photon colliders, being essentially a W pair factory, could make a useful contribution in that respect.

Before going into the heart of the subject and to give a first idea of the possibilities of $\gamma\gamma$ colliders, I will present the main characteristics of high-energy $\gamma\gamma$ collisions:

- Any elementary charged particle, phase-space allowing, can be produced in $\gamma\gamma$ collisions with a model-independent predictable cross-section.
- $\gamma\gamma$ gives access to the $J_Z = 0$ channel, which is chirality suppressed in e^+e^- . To test the electroweak symmetry breaking (ESB) mechanism, this means producing the Higgs as a resonance.
- $\gamma\gamma$ collisions feature very large cross-sections, which are always larger than in e^+e^- for the same energy and luminosity.

But all is not so bright, for $\gamma\gamma$ colliders also have shortcomings. First, the Higgs resonance cannot be so prominent as the Z at LEP since the coupling of neutral scalars to two photons only occurs at the loop level and is suppressed by a factor α. Second, $\gamma\gamma$ does not have the same energy as e^+e^- (the maximum energy varies between 80-90%) and the useful luminosity can be smaller than in e^+e^- . The latter is true especially if one uses beams optimized for e^+e^- coliders rather then designed specifically for $\gamma\gamma$ [3]. Finally, the photon collider is not monochromatic, although, as was discussed by Telnov, one can tune the parameters of the laser such as to have a nearly monochromatic spectrum near the maximum energy. This is done at the expense of a drop in luminosity.

Certainly, one has a great flexibility in choosing the energy, the spectrum and the polarization of the beams. The choice of spectrum will be dictated by the physics one is interested in. For example, a "peaked" spectrum where much the luminosity is concentrated over a narrow energy band would be most appropriate to study a resonance. A "broad" spectrum, one with sizeable luminosity over a wide energy range, would correspond to a multi-purpose machine useful for many processes[2]. Whatever the spectrum used, a precise knowledge of it is essential to be able to do precision measurements. More efforts in that direction are needed since recent studies have shown that going beyond the ideal spectrum of Ginzburg et al.[1] could significantly affect the region where the photons carry only a small fraction of the initial beam energy. This region is particularly sensitive to multiple scattering and nonlinear effects[4]. For lack of a more realistic spectrum, most of the results presented here use the ideal one.

2 Typical electroweak cross-sections

A comparison of a few characteristic cross-sections in $\gamma\gamma$ with the corresponding same final-state processes at e^+e^- clearly show the advantage of the former. Indeed, independent of the spin of the particle and at the same centre-of-mass energy, $\gamma\gamma$ -initiated processes are, at high enough energy, about an order of magnitude larger than the corresponding e^+e^- reactions (Fig. 1). Even the reaction $\gamma\gamma \to ZZ$ [5, 6], which is purely a loop effect, rapidly overtakes the corresponding tree-level e^+e^- process. This is due to the rescattering effect $\gamma\gamma \to W^+W^- \to ZZ$. Vector-boson production dominates in $\gamma\gamma$ collisions due to the t-channel spin-1 exchange. Most prominent is the W pair cross-section, which very quickly reaches a plateau of almost 90pb. This process is so important that it triggers a host of higher order processes like triple vector production ($\approx$ 1pb), 4 vector production ($\approx 100fb$) or H production via WWH [7].

Figure 1: *Typical sizes of non-hadronic $\gamma\gamma$, $e\gamma$ and e^+e^- processes. The subscripts in Higgs(top) processes refer to the mass of the Higgs(top).*

Large cross-sections are great, but more is required to do interesting physics. A drawback of $\gamma\gamma$ processes, especially as regards ESB tests is the small fraction of longitudinal vs transverse W's. While there is a large sample of W_LW_L (in fact more then 5 times than in e^+e^-), the extraction of these longitudinals from the transverse background is an arduous task. Since most transverse W's are produced quite forward, imposing angular cuts improves the situation significantly (see Fig. 2). Nevertheless, the ratio LL/TT remains higher in e^+e^- . The problem just alluded to is in fact characteristic of all processes that will be discussed for ESB tests in $\gamma\gamma$: the extraction of a signal, usually in the longitudinal sector, from a large transverse background.

Figure 2: *Comparing the total WW cross-sections and the longitudinal W_LW_L in e^+e^- vs $\gamma\gamma$.*

3 Electroweak symmetry breaking

The various options for symmetry breaking can be divided into two classes: light Higgs ($m_H \leq 800GeV$) or no Higgs (for the discussion here this is equivalent to a heavy Higgs).

The implications for electroweak physics differ markedly according to the option one is willing to consider. A light Higgs probably means the existence of supersymmetry unless one is ready to give up the naturality argument raised to avoid the large fine-tuning necessary for the elementary scalar to remain light to all orders. In this option the physics issues at a collider, in particular the PLC, would be the search for the Higgs and measurement of its properties, the search for other supersymmetric particles and determination of their properties, and precision measurements in order to see indirect effects of new physics. An example of the latter is the measurement of the trilinear couplings, $WW\gamma$. These topics can be covered at moderate energies linear colliders ($\sqrt{s_{ee}} = 300 - 500GeV$)

If the light Higgs does not exist, then ESB is triggered by strong forces, the scale being set by $\Lambda = 4\pi v \approx 1$ TeV. Although the details of the model are not known there must be new physics at this scale (e.g. technicolour, strongly-interacting particles). In particular, this new physics would show up in W self-interactions or in $W_L W_L$ scattering. The connection between heavy Higgs and longitudinal W's is best established via the process $W_L W_L \rightarrow W_L W_L$. In the SM the Higgs is introduced to cure the bad high-energy behaviour of this amplitude; nonetheless $W_L W_L$ interactions become strong if $m_H \approx .8 - 1$ TeV. The physics of the heavy Higgs is most relevant for TeV linear colliders.

Since no model has gained a consensus to describe the strongly-interacting electroweak sector, one must strive for a model-independent description of this sector. One approach, which is valid up to some scale Λ, uses an effective chiral Lagrangian. Assuming a custodial $SU(2)$ symmetry to ensure that the parameter $\rho \approx 1$, new physics in the weak boson sector is described by nonrenormalizable terms suppressed by powers of $1/\Lambda$,

$$\mathcal{L} = \mathcal{L}_{SM}(noHiggs) + \sum \frac{1}{\Lambda^n} \mathcal{L}_n \tag{3.1}$$

The leading order chiral Lagrangian, $\mathcal{L}_2$, contains only the mass terms for the vector bosons while the Next-to-Leading order, $\mathcal{L}_4$, contains the self-interactions. This includes trilinear or quartic interactions of massive vector bosons and at most one photon[8]. Self-interactions including two photons only appear at higher order, $\mathcal{L}_6$.

The effective Lagrangian formalism would break down if the scale at which the experiment is performed is sufficient to produce new resonances. These must be explicitly incorporated, the cases of either a scalar, vector or tensor resonance will be considered. The scalar one (σ-like) is representative of a heavy Higgs while the vector one (ρ-like) occurs in technicolour.

To cover all standard and non-standard manifestations of symmetry breaking, the strategy at the future collider must include: tests of W self-interactions and of longitudinal vector-boson scattering, the search for the Higgs in the whole range of possible masses, as well as searches for other heavy resonances. All these aspects can be tackled at a photon collider, as will be described in the rest of this talk.

4 $\gamma\gamma \to W^+W^-$ and W self-interactions

The importance of this process cannot be over-emphasized considering the large cross-section involved. Although the bulk of the reaction is due to the gauge transverse sector, the fact that there are so many W's around makes this reaction the ideal place to conduct precision tests of the electromagnetic couplings of the W. In the effective chiral Lagrangian description of Higgsless models, the anomalous trilinear couplings invoke two C and P conserving operators at Next-to-Leading order, L_{9L} and L_{9R}, and one C and P violating operator L_C[8]. The latter affects only ZWW and γZWW interactions while only the combination $L_{9L} + L_{9R}$ contribute to γWW. The L_i operators are expected to be $\mathcal{O}(1)$.

There is an extensive literature [2] on the effect of anomalous couplings in various experiments. Comparisons of different analyses have shown that a 500 GeV linear collider with a luminosity of $10 fb^{-1}$ does significantly better then the LHC for trilinear couplings. Furthermore, the limits that can be obtained in $\gamma\gamma$ at this energy, $|L_{9L} + L_{9R}| < 10$ represent a 50% improvement over e^+e^- [8]. This is shown in Fig. 3. However, this result is not sufficient to reach the level where one expects new physics to set in. In e^+e^- it was shown recently[9, 10] that meaningful limits could be obtained with a luminosity $\mathcal{L} = 50 - 80 fb^{-1}$. It remains to be seen if the same can be done at a $\gamma\gamma$ collider. For that one needs to generate the four-fermion final state from the decay of the W's, while keeping the full spin-correlation.

Figure 3: *Comparison between the expected bounds on the two-parameter space* (L_{9L}, L_{9R}) *at the NLC500, LHC and LEP2. We also show ("bars") the limits from a single parameter fit.*

A $\gamma\gamma$ collider can do more than precision tests on γWW. It is also sensitive to ZWW couplings through processes with three particles in the final state, for example $\gamma\gamma \to WWZ$[11], $e\gamma \to eWW$ and $e\gamma \to \nu WZ$. The latter is very sensitive to the operator L_C[12]. The limits obtained, $L_C < 25$ at 500 GeV are comparable to the ones from $e^+e^- \to W^+W^-$[13]. Furthermore, the sensitivity increases rapidly with energy.

4.1 Effect of radiative corrections

When doing precision tests one must worry about the effect of radiative corrections that could mimic those of the new couplings. Recently the complete one-loop SM corrections for helicity amplitudes for $\gamma\gamma \to W^+W^-$ were calculated[14]. It turns out that the radiative corrections for this process are theoretically clean due to the absence of most universal leading corrections. The running of α is irrelevant since we are dealing with on-shell photons, all uncertainties due to $\log(m_q^2)$ terms in small masses disappear, and there are no large log corrections associated with colinear photons except at very high energies. Furthermore, the corrections are not very sensitive to either M_t or M_H except near the resonance. Although some helicity amplitudes receive huge corrections, they are precisely the ones that contribute very little to the total cross-section. Typically radiative corrections between $1 - 10\%$ at $\sqrt{s_{ee}} = 500$ GeV are obtained, and they tend to increase with energy ($\approx 20\%$ at 1 TeV). In any case, the inclusion of radiative corrections are not expected to change much the previously obtained results on measurements of trilinear couplings.

Considering the large numbers of W's available, there are other interesting questions that can be studied in $\gamma\gamma$ which I have not addressed here. Among them are the possibility of direct tests of quartic couplings involving photons[15], CP tests in W decay and measurement of the Wtb coupling which could also give some clues about symmetry breaking.

5 Higgs searches

One of the most attractive motivations for doing physics with very energetic photon beams is the unique capability of this mode for producing a scalar particle, such as the Higgs, as a resonance. I have already mentioned that the coupling of the Higgs to two photons occurs only at the loop level. It should be emphasized that a precision measurement of the $H\gamma\gamma$ coupling is an indirect way of revealing all massive charged particles that could be present in an extension of the standard model. These heavy quanta would not decouple and would contribute to the production rate in $\gamma\gamma$.

While many processes are sensitive to the presence of the Higgs (see Table 1), the prime interest of the photon mode lies in the Intermediate Mass region †. For such a Higgs, the main decay mode is into $b\bar{b}$. Although a search is feasible at LHC, it will be a difficult and long task to extract a signal in this case. For heavier Higgs masses the resonance can be seen in the WW [16] or ZZ channel. However, the usefulness of these modes is tamed by the presence of large backgrounds from transverse vector bosons. Ultimately, for a Higgs above 400 GeV, and regardless of the energy available for the PLC, one would have to resort to other channels such as associated Higgs production or WW fusion (via the process $\gamma\gamma \to WWWW$).

Table 1: *Processses for Higgs searches at PLC and other colliders*

Mass	Collider	PLC	$\sqrt{s_{ee}}$
$M_H < 65GeV$	LEP	Ruled out	—
$65GeV < M_H < 90GeV$	LEP2	$\gamma\gamma \to H \to b\bar{b}$	$.1 - .5$ TeV
$90GeV < M_H < 140GeV$	NLC	$\gamma\gamma \to H \to b\bar{b}$	$.2 - .5$ TeV
$140GeV < M_H < 200GeV$	LHC	$\gamma\gamma \to H \to WW$	.5 TeV
$200GeV < M_H < 400GeV$	LHC	$\gamma\gamma \to H \to ZZ$	1 TeV
$400GeV < M_H < 700GeV$	LHC	$\gamma\gamma \to WWWW$	2 TeV

† $\gamma\gamma$ is also very useful in the mass range below 90 GeV, a case can be made for building a low-energy dedicated $\gamma\gamma$ collider in the event of a discovery of the Higgs at LEP2.

5.1 Intermediate Mass Higgs

For the IMH, $\gamma\gamma$ can contribute in the discovery mode or perform precision measurements of its properties. A crucial point relates to the choice of the spectrum and polarization used. Since the Higgs is produced only in the $J_z = 0$ channel, polarization plays a crucial role in enhancing the signal over background. Assuming the Higgs has been found and its mass measured, one could tune the energy of the collider and the parameters of the laser such that the peak of luminosity lies precisely at $\sqrt{s_{\gamma\gamma}} = M_H$. This is obviously the preferred way to operate when measuring $H\gamma\gamma$, though one has to realise that good luminosity is required. Early estimates for a 500 GeV collider and a luminosity of $\mathcal{L} = 20 fb^{-1}$ give a 10% precision on the width,[17] the effect of background from one radiated gluon is discussed by Khoze [18]. One disadvantage of operating in that mode is that the PLC would be run at energies much below the nominal e^+e^- energy, precluding the study of interesting processes such as the W pair production and other W reactions that could occur at higher energy. Furthermore, this low-energy narrow-band scheme could render kinematically inaccessible some of the particles that would only be probed indirectly in $H\gamma\gamma$, not to mention that the $\gamma\gamma$ mode, when operated in the full range of energy, can access scalar particles that would be kinematically out of reach in the e^+e^- mode.

If one would have two interaction regions, one devoted to $\gamma\gamma$ the other to e^+e^- , and if the Higgs has not been found elsewhere, $\gamma\gamma$ could be used to search for the Higgs. The method that allows for simultaneous studies of processes at high energy consists of running the PLC using a "broad" spectrum so that one would have reasonable luminosity over a range of energies.

The main problem in the Higgs searches, whatever the scheme used, lies in the large background. The prominent one comes from direct QED $\gamma\gamma \to q\bar{q}$ production where $q = b$ or other light quark flavours, in particular charm. However this background can be dealt with since the bulk of the cross-section is in the forward direction, so that a modest angular cut could efficiently suppressed this background and would almost totally eliminate its $J_Z = 0$ contribution. Therefore a spectrum with a predominantly $J_Z = 0$ component would both enhanced the signal and reduce the background.

When the PLC is run in the "broad" spectrum mode there are other more important backgrounds that have to be taken into account[19, 20]. They arise from the hadronic structure of the photon which can resolve into a gluon or a quark with some spectator jets left over. One then has to worry about $q\bar{q}$ production through γg as well as a host of 1-resolved and 2-resolved process. These backgrounds dominate the signal. However, since most of the resolved events are very boosted, judicious cuts can reduce it to a manageable level. It was shown, using the ideal spectrum, that at 500 GeV with $\mathcal{L} = 10 fb^{-1}$, one could obtain a good signal for $M_H = 110 - 140$ GeV [20]. Furthermore, the situation improves for a collider of lesser energy, due to the reduced resolved background. For example, at 350 GeV a signal is easily extracted for the whole IMH range. Of course this assumes the ideal spectrum. However, for the masses considered, the signal falls in the region where the spectrum is most severely affected by effects of multiple scattering and nonlinear effects. These questions should be reassessed taking these effects into account as the conclusions could differ drastically.

There have been suggestions to determine directly the parity of the Higgs using linear polarizations of the photon[21]. Since the degree of linear polarization is never very large ($< 30\%$), this always requires large luminosities, $\mathcal{L} = 100 fb^{-1}$.

5.2 Associated production

For the IMH, it will be hard to unravel a peak formation if the collider energy is greater than 500 GeV. As will be discussed in the next section, the resonance will remain hidden for heavier Higgs ($M_H \geq 400$ GeV) even if one uses the most favourable channel, ZZ. Fortunately, other efficient mechanisms for Higgs production are available, in particular the radiation of a Higgs from a W pair. This is to be expected since the cross section for W pair production is so large and the Higgs couples preferentially to the weak bosons. In fact, at 1 TeV, before folding with the luminosity spectrum, the $e\gamma$, $\gamma\gamma$ and Bjorken process are comparable for all Higgs masses[7]. However, the $\gamma\gamma$ production mode is suppressed when including a more realistic photon luminosity spectrum. Still, at 1 TeV one obtains a measurable cross-section ($\sigma > 3fb$) for $M_H < 400 GeV$.

5.3 $\gamma\gamma \to ZZ$

At first this reaction was believed to provide a background-free environment for either Higgs production or non-standard physics signals in $Z_L Z_L$ since it is purely a loop process in the $\mathcal{SM}$. The first full calculation by Jikia[5] of the one-loop process $\gamma\gamma \to ZZ$ within the $\mathcal{SM}$ dampened this enthusiasm since it turned out that, once again, the transverse modes are overly dominant, especially at high energy. This is due essentially to the W loops, the WW produced in $\gamma\gamma$ rescatter into ZZ. At $\sqrt{s_{ee}} = 400$ GeV, the Higgs resonance is clearly evident over the TT continuum all the way up to the kinematic limit. With $\sqrt{s_{ee}} = 500$ GeV, it already becomes difficult to extract a Higgs with $M_H \sim 350$ GeV. [5] To obtain these results, Jikia used a predominantly $J_Z = 0$ spectrum that is peaked towards the maximum $\hat{s}_{\gamma\gamma}$, this is not the optimum choice. With a broader spectrum featuring a dominant $J_Z = 0$ for small M_{ZZ}, one could still see a peak in the M_{ZZ} invariant mass for Higgs masses up to 400 GeV at a 1 TeV e^+e^- machine [6]. From the perspective of observing the Higgs resonance beyond TeV e^+e^- energies, the situation becomes totally hopeless as the transverse ZZ are awesome[5].

6 Strongly-interacting electroweak sector (SEWS)

If the Higgs is not found at LHC, or in the sub-TeV version of NLC, we will be in the realm of the SEWS. This sector would be probed most efficiently at TeV energies through the reaction $V_L V_L \to V_L V_L$ ($V = W$ or Z). In this channel one would either search for a resonance or, if the energy is not sufficient, for new interactions such as the ones described by the effective chiral Lagrangian.

The V pair-production processes could be regarded as the testing ground for possible rescattering effects in $WW \to VV$ that originate from the symmetry breaking sector. Unfortunately, at high energies, *i.e.*, at high VV invariant masses, where the effect of the New Physics would be most evident, one has to fight extremely hard against the background for transverse W and Z. Indeed, recent analyses have shown that while it might be possible to see effect of a tensor resonance, a scalar one as well as indirect effects are hopeless[22].

One then has to resort to the only source of longitudinal vector bosons, the ones taking part in the fusion process and contributing to $WWWW$ or $WWZZ$ production. This process is the analog of $e^+e^- \to \nu\bar{\nu}W^+W^-$ and was originally believed to be more favourable due to a presumed larger W_L content in the photon than in the electron. While it is true that in the photon there is an additional structure function corresponding to the spectator W_L, the dominant contribution is from transverse spectator W's. The latter features basically the same structure function as in the electron, except for an overall factor[2]. One would therefore expect that $\gamma\gamma$ should be comparable to e^+e^- at the same energy and luminosity. This conclusion was born out by two independent exact calculations of this $\mathcal{SM}$ process [23, 24]. The signal of a heavy Higgs is a significant increase in the channels with at least three W_L. To extract a signal requires tagging all four W's, the spectator ones being associated with the low p_T and the longitudinal ones with the central W's. The spectators are tagged with one hadronic and one leptonic decay while the central ones go into four jets. The results of the analysis showed that a 2 TeV PLC ($\mathcal{L} = 10 fb^{-1}$) would give a good signal ($S/\sqrt{B} \approx 10$) for a heavy Higgs-like scalar of 1TeV[24]. This is comparable to the e^+e^- process. However, the inclusion of the spectrum has a dramatic effect and a linear collider of 2 TeV in the e^+e^- center of mass with $\mathcal{L} = 200 fb^{-1}$ is needed to reach the same significance level.

Another interesting conclusion from these calculations is that a signal for a Higgs of 400-700 GeV can easily be seen with $\sqrt{s_{ee}} = 1.5$ TeV and $\mathcal{L} = 200 fb^{-1}$. The PLC can therefore cover the whole mass range for light or heavy Higgs searches provided a good choice of energy and spectrum is made, although precision measurements are possible only for light Higgs ($M_H < 120 GeV$).

7 Search for new particles: supersymmetry

As the best motivated alternative to the standard model, one should investigate the consequence of supersymmetic models. Supersymmetry would provide a natural framework for light Higgses. The three neutral scalars of supersymmetric models, h,H,A (pseudoscalar) could be produced as a resonance in $\gamma\gamma$. This reaction would then extend the reach in mass of e^+e^- since in the latter H and A can only be produced together and require $\sqrt{s_{ee}} > M_H + M_A$. At $\sqrt{s_{ee}} = 500$ GeV, using the $b\bar{b}$ mode, this gives the following discovery region for the supersymmetric scalars[25]: 110 GeV$< M_H <$ 200 GeV and 100 GeV$< M_A < 2M_t$. Recently, it was pointed out that this was true only if scalars decayed primarily via $\mathcal{SM}$ final states. Otherwise the above limits require high luminosities $\mathcal{L} > 60 fb^{-1}$[26].

The $\gamma\gamma$ collider can search also for other supersymmetric particles [27],the production cross-sections being universal, were already shown. Typically, one finds that $\gamma\gamma$ can have good cross-sections but offer little advantage over the e^+e^- mode, in part because of the lower achievable energy. It is for selectron searches in $e\gamma \to \tilde{e}\tilde{\chi}$ that the laser scheme becomes extremely useful, as the discovery of a selectron of $m_{\tilde{e}} \approx \sqrt{s_{e\gamma}}$ is possible.

8 Conclusion

A $\gamma\gamma$ collider of energy ranging from .2 to 2 TeV should prove to be a useful tool for probing the electroweak symmetry-breaking sector through either Higgs searches or W physics. It is unique in producing a scalar on resonance and is complementary to an e^+e^- collider in many processes.

Acknowledgements

I am most grateful to my friends and collaborators Marc Baillargeon and Fawzi Boudjema for all the work on electroweak physics issues. I also thank George Jikia for kindly supplying the curves for $\gamma\gamma \to WWWW$.

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