$\gamma\gamma$ Physics at Linear Colliders

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Abstract

A high-energy lepton-lepton collider will give us a unique possibility to study eγ and $\gamma\gamma$ interactions at high energies. The high-energy photons can be generated by Compton back-scattering of laser light on the high-energy lepton beams. With slightly reduced luminosities for eγ and $\gamma\gamma$ collisions compared to the lepton-lepton collider one, unique and complementary studies can be performed. A linear lepton-lepton collider also offers other photon sources that will be considered. We will focus on the complex properties of the photon itself and discuss some possibilities to gain new insight in its interactions at high energies and how to reveal the structure of it.

1 Introduction

A linear lepton-lepton collider is the natural continuation of the program at CERN and the Photon Physics aspects of the ep program at DESY. If there will be a possibility to study high energy collisions dedicated (partly) to photon interactions within a near future, this may well be the only opportunity.

Assuming a lepton-lepton collider being built, the annihilation processes will be overwhelmed by a background from photon processes, which clearly have to be taken seriously although they may not be of primary interest. A better understanding of the nature of the photon is thus wanted not only from a photon physics point of view.

With Compton laser back-scattering of photons [1], luminosities for eγ and $\gamma\gamma$ collisions would be not much smaller than the lepton-lepton one at typical center-of-mass energies. Several processes of great interest have a much larger cross section when involving photons than just leptons. A $\gamma\gamma$ (eγ) collider is then not only complementary but also highly competitive to a lepton-lepton one.

eγ and $\gamma\gamma$ interactions provide one of the most complex test grounds for QCD at high energies. Going to higher energies than now reachable by LEP will clearly also take us to previously unexplored regions in x and Q^2 of the photon structure function. However, an overlap with LEP measurements is highly desirable and special effort should be taken in order to obtain that.

Some important aspects of Higgs physics can be studied in $\gamma\gamma$ interactions and with a much higher accuracy than for the lepton-lepton case [2]. With Compton back-scattered photons it is possible to perform energy scanning and to focus on particularly interesting

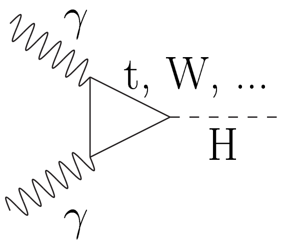

Figure 1: Resonance production of a Higgs boson.

energies. The resonance production of a Higgs boson, Fig. 1, is built up by a loop of charged particles that couples to the Higgs. When at right energy, the cross section for Higgs production is much larger in the case of $\gamma\gamma$ than for ee. The decay width of the Higgs into two photons reflects the spectrum of heavy charged particles where the probed masses may possibly be far above the Higgs mass itself.

In the electroweak sector, multiple gauge boson couplings can be studied. The pair production process $\gamma\gamma \to W^+W^-$, which has a much larger cross section for $\gamma\gamma$ than the corresponding ee one, can be used to determine properties as the static magnetic and electric multipole moments of the W bosons.

In the following, we will concentrate on the photon itself: its properties at high energies and the sources of photons at a linear lepton-lepton collider.

2 Sources of Photons

There are essentially three different sources of photons at a linear lepton-lepton collider: bremsstrahlung, beamstrahlung and Compton laser back-scattering. The latter one will probably require a separate interaction region.

High-energy accelerated charged particles radiate photons, so called *bremsstrahlung* photons, which are often utilized at e^+e^- colliders for doing $\gamma\gamma$ physics, Fig. 2. It offers a spectrum of different photon energies and virtualities. The distributions are peaked at the lower end so studies of the interesting collisions of energetic and highly virtual photons are limited by statistics. Collisions of almost real photons can be isolated by antitagging conditions of the outgoing leptons. The method suffers from not knowing the invariant mass of the $\gamma\gamma$ system, which then needs to be reconstructed from the particles observed in the detector.

A beam of charged particles may, in the presence of an external field, such as another beam of charged particles, coherently emit real photons. This is refered to as *beamstrahlung* and is a draw-back for the normal e^+e^- program, wherefore lepton-lepton colliders are designed to minimize this effect. Depending on specific design parameters, such as the beam geometry, the beamstrahlung spectrum can be made much harder than the corresponding bremsstrahlung one [3].

Compton laser back-scattering provides an intense beam of high-energy photons. The idea is to have a laser beam incident on a high-energy lepton beam. With sufficient laser flux, almost all of the energy of the incident lepton will be transferred, via the Compton process, to the scattered photon. If the invariant mass of the incident lepton and the laser photon system is too high, the pair production process $e + \gamma_{\text{laser}} \to e + e^+ + e^-$ will occur. Similarly, a too high invariant mass of the scattered photon and the laser photon system will allow the process $\gamma + \gamma_{\text{laser}} \to e^+ + e^-$. Both processes can be suppressed by tuning the frequency of the laser; the latter of the two processes is often the one setting

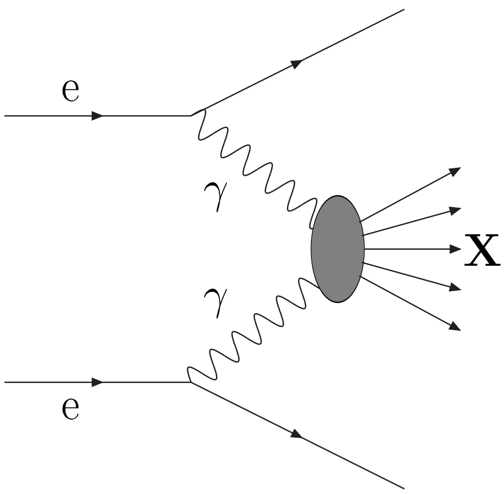

Figure 2: $\gamma\gamma$ process induced by bremsstrahlung from the incoming leptons.

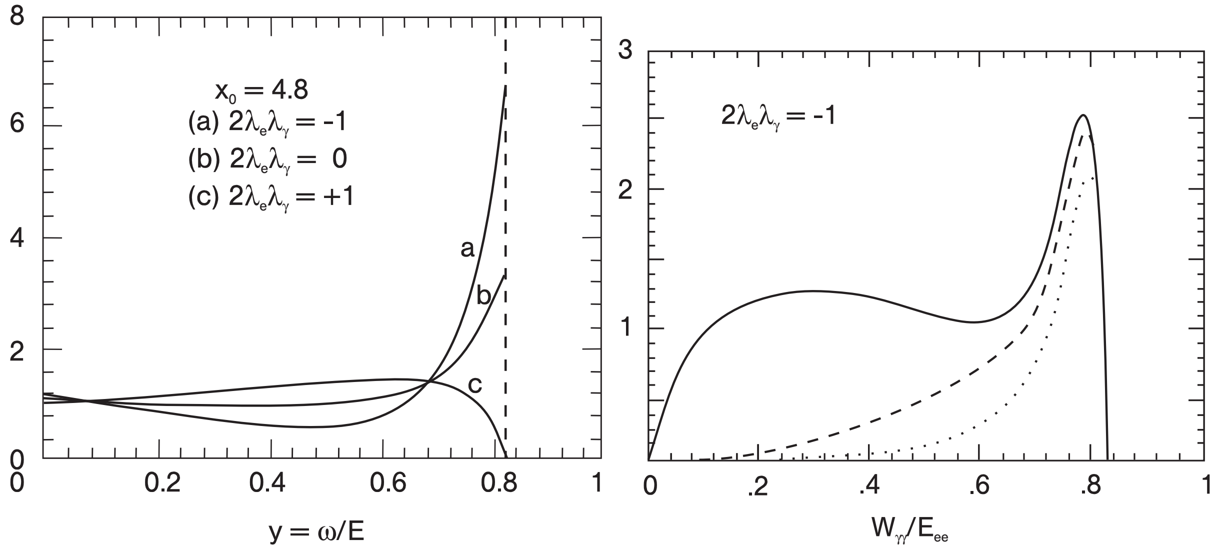

Figure 3: To the left, the energy fraction spectrum of the Compton laser back-scattered photons for different helicities of the incident lepton and laser photon beams [2]. To the right, the invariant mass distribution of the $\gamma\gamma$ system for the case of opposite helicities of the lepton and laser beams. The dashed lines show the distribution when the distance between the conversion and collision point are separated.

the upper limit.

The energy spectrum of the high-energy photons is rather broad for unpolarized beams. For polarized beams it can be made much sharper, as illustrated in Fig. 3. The case of opposite helicities of the incident lepton and laser beams give a peaked distribution towards the upper end.

There is a strong energy–angle correlation for the Compton scattered photons. By varying the distance between the conversion and collision point of the photons, a very peaked invariant mass spectrum for the $\gamma\gamma$ system can be obtained, Fig. 3.

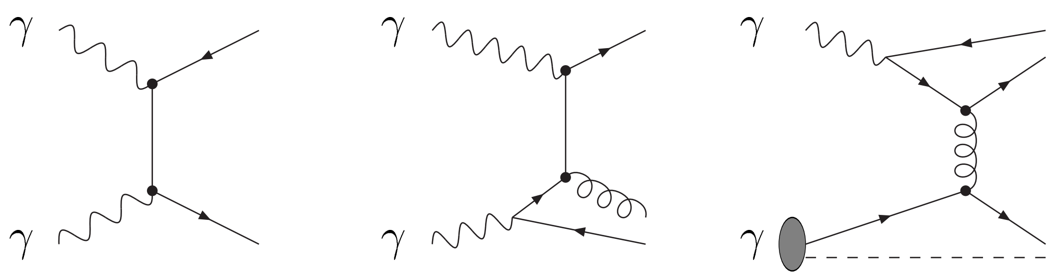

Figure 4: Examples of a direct, a single-resolved (a direct and an anomalous photon) and a double-resolved (an anomalous and a VMD photon) event in $\gamma\gamma$ collisions.

3 Nature of Photon

The photon is often refered to as not having any internal structure. This is true for highly virtual photons, as in DIS of ep. For a real photon this pointlike behaviour corresponds to one of its components, called the direct photon. At high energies the photon may also fluctuate into a virtual $q\overline{q}$ pair which then may undergo strong interactions in a collision, this is the so-called resolved photon.

The resolved photon may be further divided into low- and high-virtuality fluctuations. The high-virtuality ones, the anomalous photons, are calculable from perturbative QCD whereas the low-virtuality fluctuations are not. Instead, they can be approximated by Vector Meson Dominance models (VMD), where the photon couples directly to a vector meson state which has the same quantum numbers as the photon, i.e. ρ, ω, ϕ, etc. The couplings of the photon to the vector mesons are determined experimentally. It is then necessary with an effective description of the photon in terms of an *a priori* unknown parton distribution [4].

In common for the resolved photon components is that they leave a beam remnant behind in a collision. At leading order, all of the energy from the direct photon goes into the hard interaction. This is reflected in the x_γ observable, which is defined as the fraction of the photon lightcone momentum that goes into the production of jets. Direct photon events have $x_\gamma = 1$ but various effects smear out the distribution to lower values.

A hard-scattering $\gamma\gamma$ process can then be classified according to the number of photons being resolved, Fig. 4. The direct process $\gamma\gamma \to f\overline{f}$ is the ordinary fermion pair production process. With one or both photons resolved, the hard scattering-processes should be convoluted with the parton distribution of the resolved photon. The single-resolved processes correspond to the direct ones in γp, and the double-resolved ones to resolved processes in γp.

4 $\gamma\gamma$ total cross sections

The $\gamma\gamma$ total cross section is not known from first principles and is poorly measured so far [5]. The situation is even worse for the case of mildly virtual photons. When measuring the $\gamma\gamma$ total cross section from the process $e^+e^- \to e^+e^- +$ hadrons, i.e. using bremsstrahlung photons, antitagging conditions have to be applied for the scattered leptons. The invariant mass $W_{\gamma\gamma}$ of the $\gamma\gamma$ system then has to be reconstructed from the finally observed particles. The method of unfolding is used for estimating the correct invariant mass from the measured one. Since a large fraction of the final-state particles

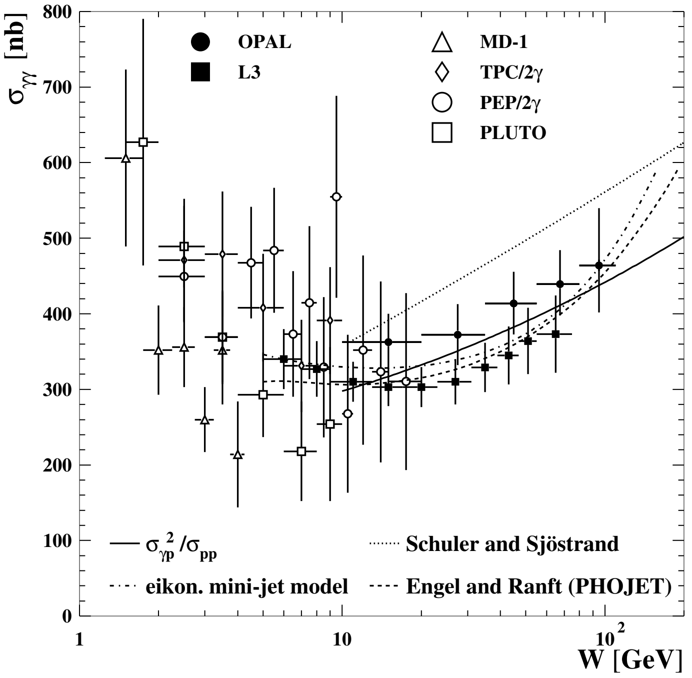

Figure 5: $\gamma\gamma$ total cross section. For a description of the models, see [5] and references therein. The model curve here labelled Schuler and Sjöstrand is intended as an upper limit, not a central value.

go undetected, the estimate has to be based on a sound model that hopefully describe the correct total cross section. In the end it leads to large systematic errors. In Fig. 5, OPAL have presented a result which is based on unfolding with two different models. The result of L3 is based on unfolding with one model only.

As for hadron-hadron collisions the $\gamma\gamma$ total cross section is rising with increasing energy, Fig. 5, which is consistent with a universal Regge behaviour of total cross sections. Since the $\gamma\gamma$ total cross section presumably is dominated by the hadronic component of the photon, important cross-checks can be done with γ-hadron and hadron-hadron collisions.

To obtain a better understanding of the $\gamma\gamma$ total cross section, it is important to measure it at a wide range of energies. This can be done, in principle, by Compton back-scattered photons since they can be obtained within a narrow energy interval, as described in a previous section. The problem with unfolding is not present but the number of $\gamma\gamma$ collisions per bunch crossing may be substantial, depending on the actual experimental set-up, making the interpretation of data harder than first thought of.

Recent measurements of the $\gamma^*\gamma^*$ total cross section by L3 and OPAL is in conflict with leading order BFKL calculations [6, 7]. A model with the concept of virtual resolved photons describes the data however. It may indicate that the current x-values available at LEP are too large for the summation of $\log(x)$ terms to be relevant.

5 Photon Structure

The cross section for DIS $e\gamma$ can be used to extract the F_2^γ structure function of the real photon. The parton distributions obey Q^2 evolution equations and can be written as a sum of two terms; an inhomogeneous and a homogeneous term. The (non-perturbative) homogeneous term is familiar from the proton parton distributions whereas the (perturbative) inhomogeneous one arises from the point-like coupling of the photon to a $q\overline{q}$ pair (thereof the name, anomalous photon).

To reveal the structure of the photon, a probing virtual photon can be provided by bremsstrahlung photons. Complementary studies can be obtained by charged currents in DIS $e\gamma$. Previously unexplored regions of high Q^2 can be reached. Moreover, with a small-angle tagger, an overlap with LEP measurements and previously unaccessible small values of Bjorken-x (x_{Bj}) can be obtained. This is desirable to give constraints on the poorly known gluon distribution of the photon.

The target photon can be obtained from any of the three sources previously discussed. They offer different kinematical regions, however.

To study the virtual-photon structure, available from bremsstrahlung photons, double-tagged events is needed but these occur at low rates. Again, a small-angle tagger is desirable for overlap with previous measurements.

Using bremsstrahlung photons as targets will give a large systematic error for small-x_{Bj} measurements due to the problems with an unknown invariant mass of the collision. At large-x_{Bj} the systematic errors are smaller and will give complementary measurements to those at LEP (overlapping or not).

The beamstrahlung photons can be much harder than the bremsstrahlung ones, giving access to small-x_{Bj} values — provided that there is a small-angle tagger. Furthermore, with beamstrahlung photons the event rates can be peaked at the lowest end of the x_{Bj} distribution giving reasonable statistics [3].

If both lepton beams are Compton back-scattered, interactions of high energy real photons can be studied at luminosities comparable to the lepton-lepton case. With only one beam back-scattered, deep inelastic scattering of $e\gamma$ can be used to measure the real photon structure. It is ideal for small-x_{Bj} measurements since large invariant masses are easily obtained. The systematic errors for large x_{Bj} will, of course, also be reduced with this option.

The parton content of the photon can be further explored by looking at charm production, $e^+e^- \to e^+e^- + c\overline{c}$. At lepton-lepton collider energies of 500 GeV, the single-resolved cross section is larger than the direct one and since the boson-gluon fusion process dominates the single-resolved processes; it probes the gluon structure of the photon.

6 Summary

By varying geometric parameters and the polarization of the incident lepton and laser beams, Compton laser back-scattering can be used to perform energy scanning over a broad energy range or to focus on a particularly interesting energies, such as the Higgs mass. The flexibilities and possibilities, whereof several unique ones, make a Compton collider competitive to the original lepton-lepton collider.

For measuring the photon structure, a small-angle tagger is desirable for obtaining overlapping results with LEP. The small-x_{Bj} region is outstandingly best measured with the Compton back-scattering option. This region will give access to the gluon content of the photon and will offer new stringent tests of QCD. It can also be reached with beamstrahlung photons but the performance of the measurement rely on specific design parameters of the collider.

The $\gamma\gamma$ total cross section will require a small-angle tagger to be measured with bremsstrahlung photons. Again, this can probably be done much better with Compton back-scattering, depending on the actual design of the machine.

Although photon physics may not be of primary interest at a linear lepton-lepton collider it will be one of the major backgrounds for many processes of the original e^+e^- program, and thereby an over-all better understanding of the photon and its interactions is wanted.

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