THE STUDY OF THE PHOTON STRUCTURE FUNCTIONS IN THE ILC ENERGY RANGE*

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At the future e^+e^- linear collider ILC/CLIC, it will be possible to perform the measurement of the photon structure functions in a wider range of kinematic variables x and Q^2 in comparison to that accessible to the previous experiments at LEP. The classical way to measure the photon structure functions is the study of the $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-X$ process, where X denotes the leptonic or hadronic final state. For the study of the potential of ILC to measure the QED and hadronic photon structure functions, the simulations of two-photon processes were performed at the ILC center-of-mass energy of 500 GeV using the Pythia and the ILCSoft packages. The analysis uses information from the forward detectors, the tracking detectors and calorimeters which are the parts of the planned ILD detector.

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1. Motivation and theoretical framework

The two-photon processes provide a comprehensive laboratory for exploring virtually every aspect of the Standard Model and its extensions. They serve as the prototypes of collisions of other gauge bosons, allowing to test the electroweak theory in photon–photon interactions and provide a good testing ground for studying the predictions of quantum chromodynamics (QCD). These processes could be also the source of the production of supersymmetric squark and slepton pairs. In particular, the two-photon

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process in which one of the virtual photons is very far off-shell (large virtuality), while the other is close to the mass-shell (small virtuality), can be regarded as the deep inelastic scattering of an $e^{\pm}$ on a quasi-real photon [1, 2]. This process of deep inelastic scattering is usually used to investigate the photon structure functions [3], which are analogous to the nucleon structure functions. The first measurement of the photon structure functions has been performed using the detector PLUTO at the DESY storage ring PETRA (1981) [4]. Following this pioneering work, many experiments have been performed at all high energy e^+e^- and ep storage rings [5], where the lepton beams serve as a source of high energy photons. The classic way to investigate the structure of the photon at e^+e^- colliders is the study of the process:

$$e^+e^- \to e^+e^-X$$

proceeding via the interaction of two photons, which can be either quasi-real or virtual [3]. The incoming leptons radiate photons producing a hadronic or leptonic final state X. The kinematics of these interactions is illustrated in figure 1, which also includes the definitions of the photons' virtualities

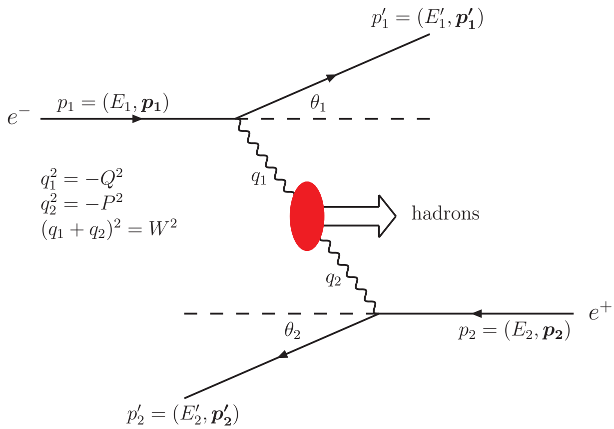

Fig. 1. Kinematics of the two photon process [5].

(Q^2, P^2) and the invariant mass squared of the $\gamma\gamma$ system (W^2). The polar angles at which the electrons are scattered are measured with respect to the direction of the beam electrons and depend on the virtualities of the photons. From the experimental point of view, the following three event classes can be distinguished:

— *anti-tagged events* — in the case where none of the scattered beam electrons can be observed in the detector; one can study the structure of a quasi-real photon in terms of total cross sections, jet production and heavy quark production;

— *double-tagged events* — both electrons are observed; the dynamics of highly virtual photon collisions is probed;

— *single-tagged events* — one electron is detected; the process can be described as deep inelastic electron scattering on a quasi-real photon.

These event classes can be studied in order to measure both the QED and hadronic photon structure functions [6]. In this paper, we focus on the study of the quasi-real photon structure, therefore the single-tagged events will be further analysed.

The usual dimensionless kinematic variables of deep inelastic scattering are the fraction of parton momentum with respect to the target photon (x) and the energy lost by the inelastically scattered electrons (y), which are defined as:

$$x = \frac{Q^2}{2q_1q_2}\,, \tag{1}$$

$$y = \frac{q_1q_2}{p_1q_2}\,, \tag{2}$$

where p_1 is the four-momentum of the primary electron, which is later scattered off the quasi-real photon with virtuality $P^2 = -q_2^2$ (q_2 is the photon four-momentum).

Experimentally, the kinematic variables Q^2, x and y are obtained from the four-momenta of the tagged electrons and those of the hadronic or leptonic final states using the information about the polar angle at which the tagged electron is scattered (see [7] for a detailed discussion) via:

$$Q^2 = 4E_{\mathrm{b}}E\sin^2\left(\frac{\Theta}{2}\right)\,, \tag{3}$$

$$x = \frac{Q^2}{(Q^2+W^2+P^2)}\,, \tag{4}$$

$$y = 1-\frac{E}{E_{\mathrm{b}}}\cos^2\left(\frac{\Theta}{2}\right)\,, \tag{5}$$

where E_{b} is the energy of the beam electrons, E and Θ refer to the energy and the polar angle of the scattered electrons.

The differential cross section can be written in terms of x and y variables [8] as:

$$\frac{d^2\sigma}{dQ^2dx} = \frac{2\pi\alpha^2}{xQ^4}\left(\left[1+(1-y)^2\right]F_2^\gamma\left(x,Q^2\right) - y^2F_{\mathrm{L}}^\gamma\left(x,Q^2\right)\right)\,, \tag{6}$$

where $F_2^\gamma(x,Q^2)$ and $F_{\mathrm{L}}^\gamma(x,Q^2)$ are the photon structure functions.

In spite of many previous studies of the photon structure, its investigation is still needed to bring our understanding of the photon to the same level as HERA has achieved for the proton. This will offer new insights into QCD. Since the beam energy accessible at the future linear collider ILC/CLIC will be higher, it is expected that the measurements of the evolution of the photon structure function can be performed in a wider range of Q^2 and x variables. It would be interesting to study the structure function for highly virtual photons, because the interaction of two virtual photons is the so-called 'golden' process to study the parton dynamics (DGLAP and/or BFKL) [9]. For this purpose, the ability to tag both scattered electrons (double-tagged events) is needed. It would also allow to determine the invariant mass squared W^2 of the $\gamma\gamma$ system independently of the hadronic final state and thus to increase the precision of the measurement of the photon structure function. Moreover, a new light on the photon structure would be shed by spin-dependent structure functions, which have not been measured so far. This would be possible in the polarized e^+e^- collisions at the future linear collider.

2. Expected values of kinematic variables

Since the beam energy at the future linear collider ILC/CLIC is planned to be higher than in the previously performed experiments, it is expected that the x variable range will be extended towards lower values. Also, extension of the Q^2 range is anticipated. The Monte Carlo simulations carried out with help of Pythia 6.4 [10] have confirmed it. The results of these simulations in the case of tagging the scattered electrons in deep inelastic $e\gamma$ scattering at the LumiCal and BeamCal detectors[1] are presented in figure 2. The cross markers are related to the generated events at the ILC centre-of-mass energy of 500 GeV. For comparison, the stars indicate the generated events at the CLIC centre-of-mass energy of 3 TeV. Furthermore, figure 3 shows the histograms which are the predictions for the distributions of x and y variables, respectively, in the case of single-tagged events at the ILC centre-of-mass energy of 500 GeV with the scattered electrons detected only at the LumiCal detector. By virtue of the weak dependence of the x distribution on the target photon virtuality, P^2, the zero value of P^2 can be assumed (as in the case of previous experiments, *e.g.* at LEP [3]). Moreover, the obtained mean value of the y variable (Fig. 3, right) is less than 0.08, thus the contribution of the term proportional to the longitudinal structure function $F_{\mathrm{L}}^{\gamma}(x, Q^2)$ in Eq. (6) is negligible. Therefore, by measuring the differential cross section, one can determine the F_2^{γ} function.

[1] The LumiCal and BeamCal are special calorimeters designed to measure the scattered electrons in the very forward direction of future detectors at an e^+e^- collider [11].

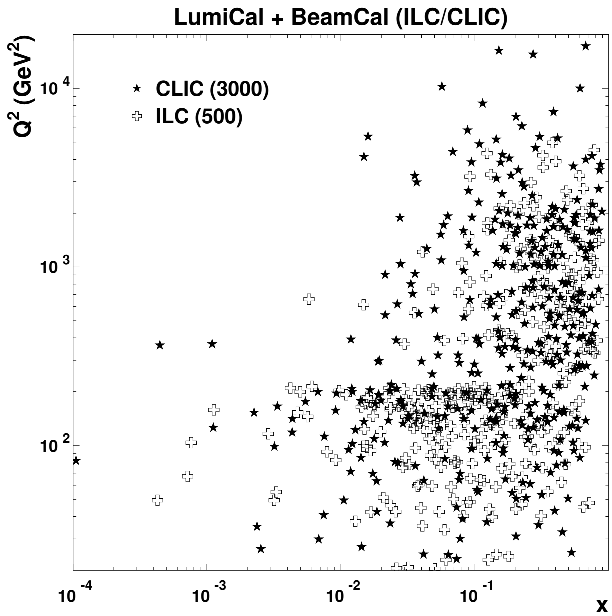

Fig. 2. Kinematical plane (x, Q^2) with simulated single-tagged events for the case of detecting scattered electrons at the LumiCal and BeamCal detectors.

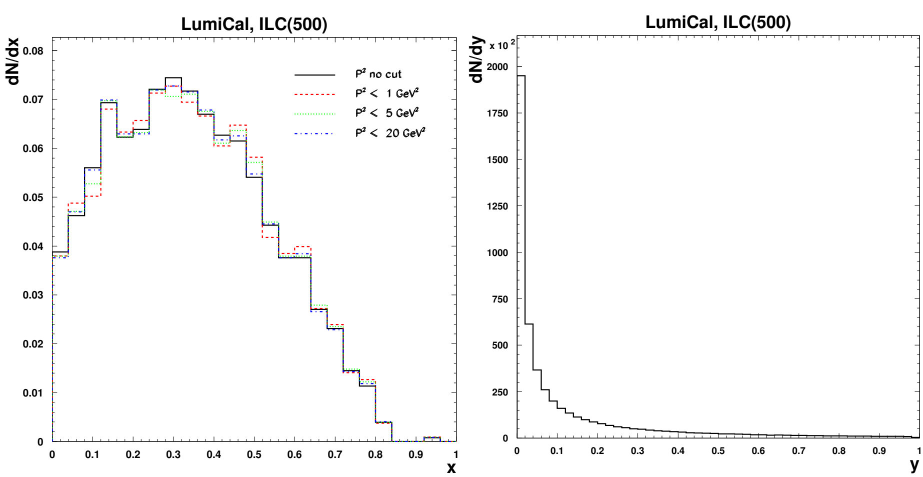

Fig. 3. (left) Distribution of x variable. The histogram is prediction from Pythia 6.4 for the case of single-tagged events at the ILC centre-of-mass energy of 500 GeV with scattered electrons detected only at the LumiCal detector. (right) As in the left drawing for the distribution of the y variable.

3. Event selection

The feasibility study of the measurement of the F_2^γ structure function of a quasi-real photon is based on the Monte Carlo simulations of single-tagged events with a leptonic (QED structure function) or hadronic (hadronic structure function) final state in the deep inelastic $e\gamma$ scattering regime. At first, the study concentrated on processes with scattered electrons measured in the LumiCal detector. Such events can be selected with the following set of cuts. Firstly, an electron candidate should be observed in the LumiCal detector with energy $E > 0.7\ E_\mathrm{b}$ and polar angle in the range of the angular acceptance of this detector, *i.e.* $31 < \Theta < 78$ mrad. The angle Θ is measured with respect to the original beam direction. Furthermore, there must be no deposited energy with value $E_\mathrm{atag} > 0.2\ E_\mathrm{b}$ in the detector on the opposite side. This is an anti-tag cut which is applied to the possible electron candidates in the hemisphere opposite to the tagged electron in order to guarantee the low virtuality of the quasi-real photon. Secondly, in the case of the determination of hadronic structure function, at least three tracks belonging to the hadronic final state have to be present. When the QED structure function is studied, the events with muons in the final state are selected since this process gives the clearest measurement. This is because for e^+e^- final state, the number of different Feynman diagrams contributing to this process makes the analysis much more difficult. On the other hand, for $\tau^+\tau^-$, the final state can be only identified by detecting the products of τ decays, which is also more difficult. Muon pairs are detected in muon detectors. Another requirement is that the visible invariant mass W_vis should be in the range of 3 GeV $< W_\mathrm{vis} < 0.6\ E_\mathrm{b}$. The upper limit should reduce the expected background from e^+e^- annihilation events.

4. First results for the F_2^γ structure function

Monte Carlo simulations indicate that the information from the LumiCal detector can be used to study the photon structure function. However, in order to extend the range of x and Q^2 variables, it is necessary to use also other detectors such as the BeamCal and ECAL [12]. This will enable the measurement of the scattered electrons in a much wider angular range. The results of Pythia 6.4 Monte Carlo studies and very preliminary results obtained using the reconstructed kinematic variables in the case when the scattered electrons are tagged only in the LumiCal detector are presented in figures 4 and 5.

The uncertainties marked on these plots are statistical only. Certainly, the systematic effects have to be estimated. This will be, besides the consideration of possible background processes, the next step of the analysis. It is also intended to compare the Pythia generator level results with predictions of other Monte Carlo generators, such as WHIZARD, HERWIG as well as those used at the LEP experiments (*e.g.* PHOJET, TWOGAM) after their adaptation to the ILC/CLIC conditions.

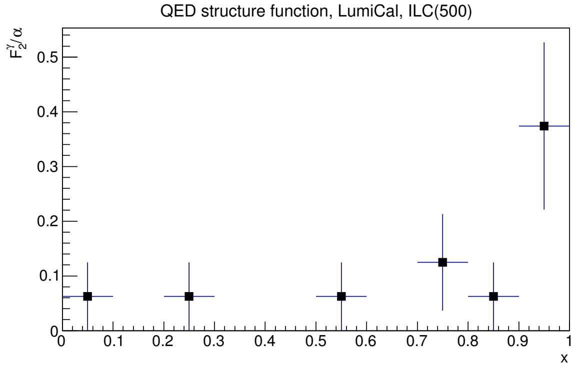

Fig. 4. The QED structure function of a photon divided by the fine structure constant as function of x variable for the mean value of Q^2 equal to 119 GeV^2 (reconstruction level). Only statistical uncertainties are presented.

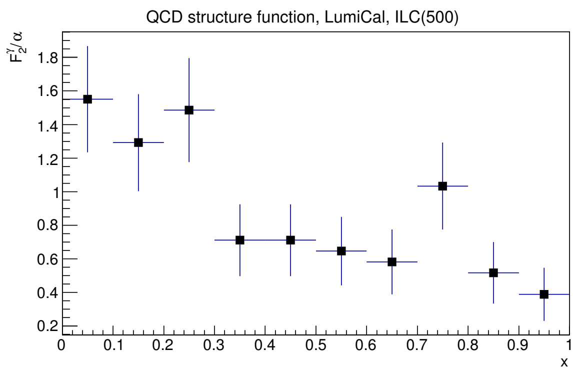

Fig. 5. The hadronic photon structure function devided by the fine structure constant as a function of x variable for the mean value of Q^2 equal to 119 GeV^2 (reconstruction level). The uncertainties are statistical only.

5. Summary

The available beam energy at the future linear collider ILC/CLIC will be higher than that accessible at previously performed experiments, so it is expected that it will be possible to study the evolution of the photon structure function in a wider range of kinematic variables. Very preliminary results for QED and hadronic photon structure functions F_2^γ were presented.

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