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# $F_2^\gamma$ at the ILC, CLIC and FCC-ee

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**Abstract**
Despite many studies of the photon structure done in the past, still lots of issues need to be investigated. Continued research in this field would greatly benefit from measurements performed at future $e^+e^-$ colliders. The potential of this field of research at the ILC, CLIC and FCC-ee is studied. In order to check the possibility of measuring the photon structure functions at future experiments, simulations of two-photon processes are performed. This paper presents the obtained results.

**Keywords**
Photon structure functions; ILC; CLIC; FCC-ee

## 1 Motivation

The earliest photons probably appeared about fourteen billion years ago, during the Big Bang. Unlike electrons and quarks, photons have no mass ($m < 1 \cdot 10^{-18}$ eV), so they can travel in vacuum at the speed of light. They are chargeless ($q < 1 \cdot 10^{-35} e$) [1] gauge bosons of quantum electrodynamics (QED) having no internal structure in the common sense. However, according to quantum field theory, the existence of interactions carried by the gauge boson means that this boson can develop some structure. A photon, for example, can fluctuate for a short amount of time to a lepton-antilepton or quark-antiquark pair. Photons can therefore interact with other particles directly as a whole or through particles produced by their quantum fluctuations. The diversity of the photons' behaviour allows us to investigate its leptonic or hadronic nature. The quantities used to describe the structure of a photon are photon structure functions.

The experiments measuring these functions have until now only been carried out at electron-positron colliders or electron-proton storage rings [2], where the lepton beams serve as the source of high energy photons. The first measurement was performed using the detector PLUTO at the DESY storage ring PETRA (1981) [3]. Following this pioneering work many experiments have been conducted, yet there are still a lot of problems to solve. Thus it is essential to continue the studies. However, the last papers containing experimental data on the photon structure functions were published in 2005. They were the papers of the two-photon working group from the L3 experiment at LEP [4]. New experimental data can be anticipated from a new linear electron-positron collider: ILC, CLIC or FCC-ee. As the beam energy at the ILC / CLIC will be higher than at LEP, it is expected that it will be possible to measure the $Q^2$ evolution of the structure function $F_2^\gamma$ in a wider range. On the other hand, although the beam energy at FCC-ee will be lower than at CLIC, thanks of its high luminosity [5] this machine will offer large statistics. Therefore, one can expect valuable results on many issues related to the photon structure function. It would be moreover interesting to study the structure function for highly virtual photons, because the interaction of two virtual photons is the so-called 'golden' process to distinguish between DGLAP and BFKL parton dynamics [6]. For this purpose, the ability to tag both scattered electrons (the so-called double-tagged events) is needed. It would allow us also to determine the invariant mass squared of the $\gamma\gamma$ system $W^2$ independently of the hadronic final state and thus to increase the precision of the measurement of the photon structure function [7]. Additionally, new light on the photon structure would be shed by spin-dependent structure functions (more details in [8,9]), which have not been measured so far.

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This would be possible in the polarized $e^+e^-$ collisions at the future colliders. Furthermore, two-photon processes are a background for physical analyses in which signals from new physics (physics beyond the Standard Model) are being searched for, therefore the knowledge of their nature is important [10].

## 2 Expected measurement capabilities

By analyzing the possibilities of measuring the structure function $F_2^\gamma$ in the experiments at the future $e^+e^-$ colliders, the expected numbers of events of deep inelastic electron-photon scattering was estimated. The estimates assumed the predicted values of luminosities for the various stages of these experiments [5, 11, 12], whereas the cross sections were determined using the Monte Carlo generator PYTHIA 6.4 [13]. The projections for the ten-month period of data collection are presented in Table 1. The number of events included in the last column of the table have been estimated assuming the detection of scattered electron at the LumiCal detector. This detector will be the luminometer of the future experiment what will be run on ILC/CLIC or FCC-ee using Bhabha scattering as the gauge process [11, 14–16].

| | sqrt(s) [GeV] | Luminosity [$10^{34}$cm$^{-2}$s$^{-1}$] | $\sigma(e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-$hadrons) [pb] | Acceptance | N(events) |
|---|---|---|---|---|---|
| FCC-ee | 90 | 68.0 | 287.8 | 0.170 | $8.6 \times 10^8$ |
| | 160 | 19.0 | 419.4 | 0.076 | $1.6 \times 10^8$ |
| | 240 | 4.9 | 540.8 | 0.042 | $2.9 \times 10^7$ |
| | 350 | 1.3 | 674.1 | 0.024 | $5.4 \times 10^6$ |
| ILC | 500 | 1.8 | 823.5 | 0.040 | $15.4 \times 10^6$ |
| | 1000 | 3.6 | 1035.5 | 0.040 | $38.8 \times 10^6$ |
| CLIC | 1500 | 3.7 | 1212.6 | 0.015 | $4.6 \times 10^6$ |
| | 3000 | 5.9 | 1425.1 | 0.015 | $8.7 \times 10^7$ |

**Table 1:** Estimated number of events of deep inelastic electron-photon scattering per 10 months of data collection at FCC-ee, ILC, and CLIC assuming tagging of scattered electrons at the LumiCal detector.

The distributions of polar angles at which these electrons are scattered are shown in Figures 1 and 2. They show clearly that with increasing beam energy, the more electrons are scattered at small angles. Therefore, they become more difficult to register in the detectors and, consequently, we lose a large number of events. Thus despite the fact that the cross section increases with the energy (cf. Fig. 3), the measurement capabilities decrease.

The kinematic variable dependent on the polar angle $\Theta$ of the scattered electron is the virtuality of the photon:

$$Q^2 = 4E_b E \sin^2\left(\frac{\theta}{2}\right), \tag{1}$$

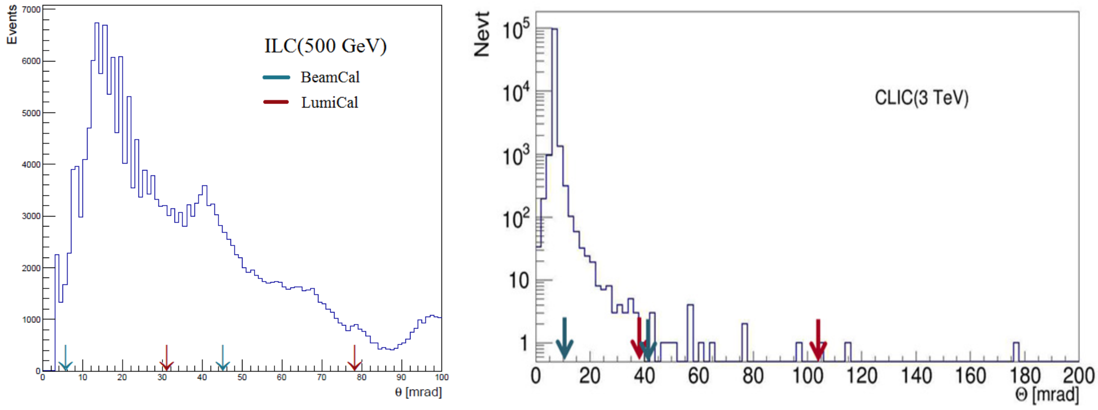


**Fig. 1:** The distributions of polar angles of scattered electrons expected in the energy range of the linear collider: ILC (left), and CLIC (right). Arrows indicate the angular acceptances for the LumiCal (red arrow) and BeamCal (blue arrow) detectors. The BeamCal will be used to measure remnants of beamstrahlung, to assist beam tuning, as well as to detect high energy single electrons [14].

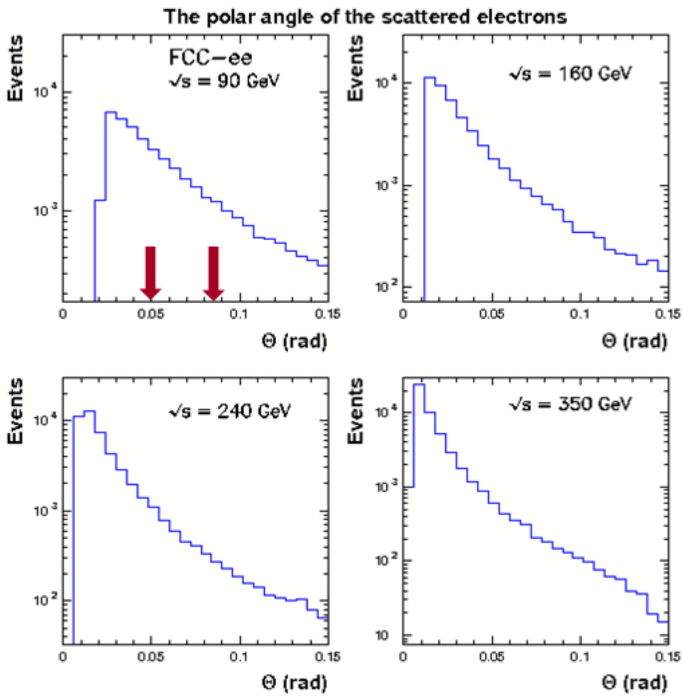


**Fig. 2:** The polar angle of the scattered electrons for energies proposed for FCC-ee project. The arrows indicate the indicative acceptance range for the LumiCal detector.

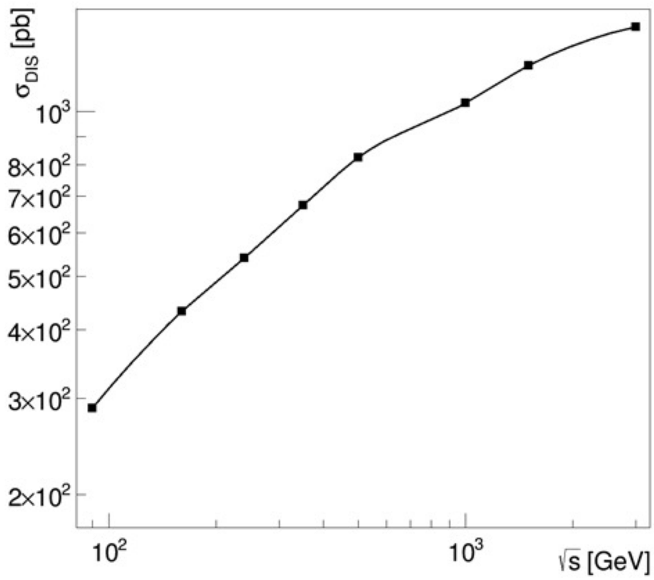


**Fig. 3:** Dependence of the cross section on the process $e^+e^- \xrightarrow{\gamma\gamma} e^-e^+$ hadrons on the center-of-mass collision energy. The results were obtained using the PYTHIA 6.4 generator.

where $E_b$ is the energy of the beam electron and E refer to the energy of the scattered electron. The $Q^2$ should take higher values for the higher beam energy, as it was confirmed by the simulations. Figure 4 shows the distributions of variable $Q^2$ obtained using three different Monte Carlo generators (PYTHIA 6.4 [13], TWOGAM (2.04) [17], HERWIG 6.5 [18]) for ILC (500 GeV) and CLIC (3000 GeV). They show a clear shift towards higher values of $Q^2$ with increasing beam energy. Also differences in the results obtained from different generators are visible. This result provides additional motivation to design future experiments to investigate photon properties, since only the experimental data will validate the models adopted in each generator.

Another kinematic variable describing the process of deep inelastic electron-photon scattering is the Bjorken variable $x$, which is determined experimentally from the formula:

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

where $W^2$ is the invariant mass squared of $\gamma\gamma$ system, $P^2$ is the virtuality of the second photon and is usually assumed to be zero. The $W^2$ is determined from the energy and momenta of the particles in the final state. It is therefore fraught with high uncertainty due to the limited detection capabilities of the produced particles (angular acceptances of detectors). The effect of the available angular ranges in which the produced hadrons are detected on the distribution of the variable $x$ illustrate the histograms shown in Figure 5. The blue colour indicates the distribution in the ideal case when all produced hadrons are seen in the detector. The red colour corresponds to the results obtained with the adoption of certain (indicated on the individual histograms) conditions for these polar angles of the hadrons. In addition, the lines in green correspond to situations where hadrons are not detected within the LHCAL angular acceptance range. LHCAL is the hadronic calorimeter proposed for ILC detectors which will measure hadrons at small produced at small polar angles. The results show that the ability to detect hadrons produced at low polar angles (e.g. using a LHCAL detector) can improve the accuracy of the measurement of the effective mass W and thus increase the precision of the determination of the variable $x$.

Determined $x$ and $Q^2$ variables were used to calculate the photon structure function. Example results of PYTHIA 6.4 Monte Carlo studies, as well as those obtained using the reconstructed kinematic variables, are presented in Figures 6 and 7.

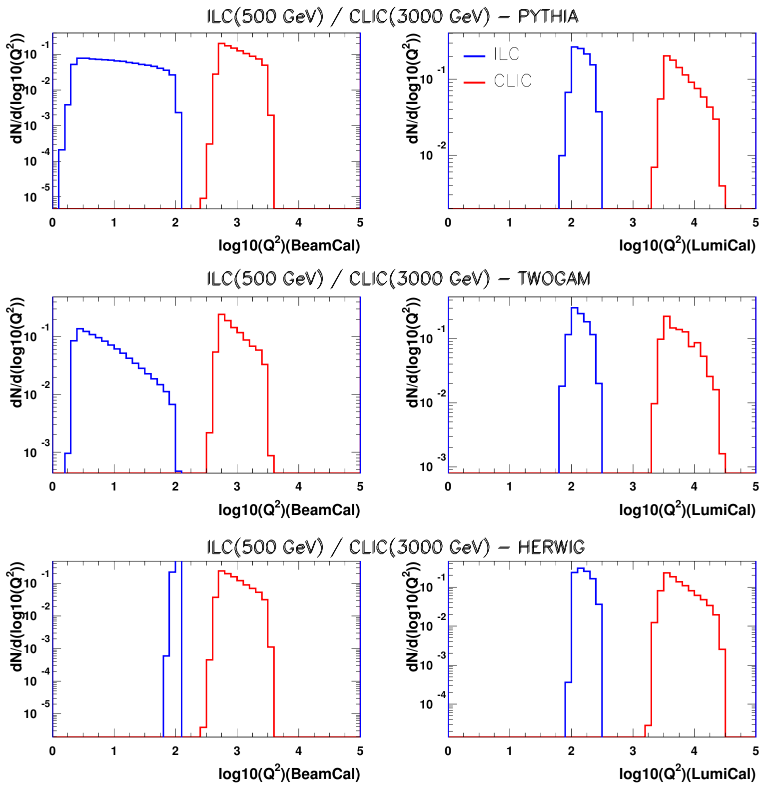


**Fig. 4:** Distributions of the variable $Q^2$ obtained using three Monte Carlo generators (PYTHIA 6.4, TWOGAM 2.04, HERWIG 6.5) for photon structure studies at the ILC(500 GeV) and CLIC(3 TeV).

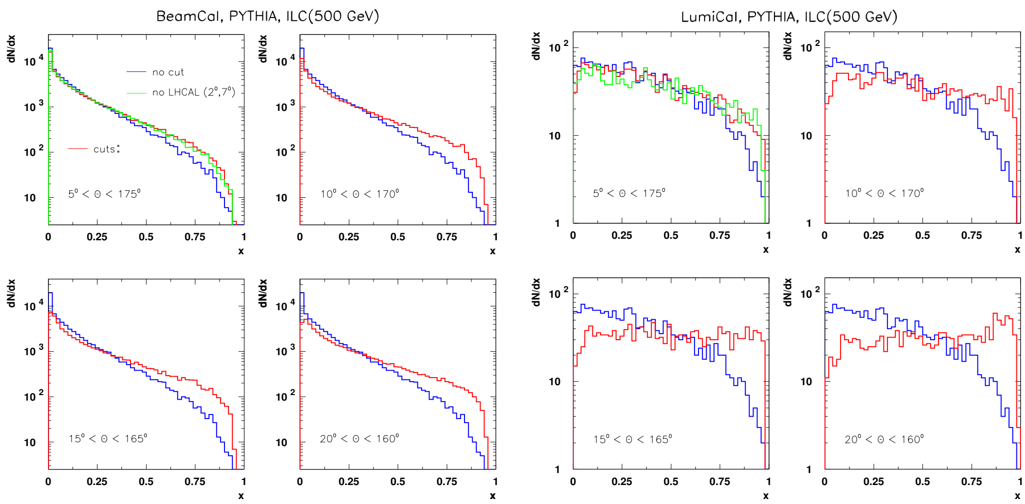


**Fig. 5:** The distribution of the $x$ variable in the case when scattered electrons are detected only in the BeamCal detector (left) and only in the LumiCal detector (right) depending on the available angular ranges within which it is possible to register hadrons produced in the process $e^+e^- \xrightarrow{\gamma\gamma} e^-e^+$ hadrons. The range 2–7 degrees was adopted as polar angle acceptance for the LHCAL detector.

The obtained results indicate that the forward detectors will allow the photon structure function in $e\gamma$ DIS processes to be measured. Available angular ranges will make it possible to obtain the functions in a wide range of $Q^2$. Since the results obtained at the reconstruction level differ from the results obtained at the generation level, it is necessary to introduce corrections due to the detector effects.

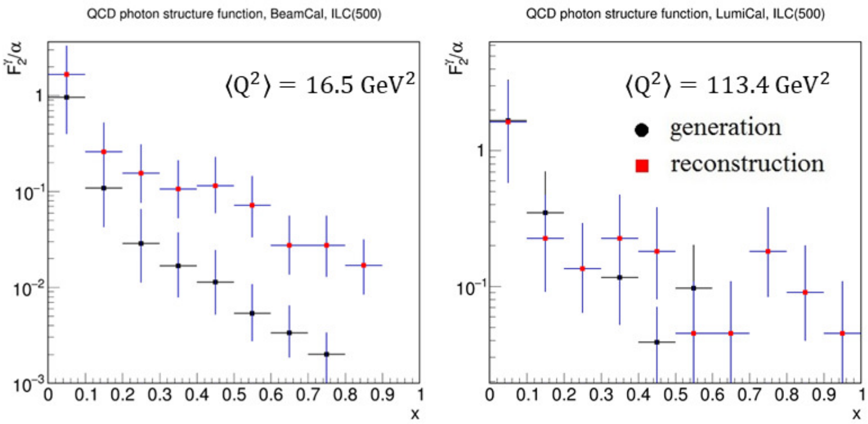


**Fig. 6:** The hadronic photon structure functions divided by the fine structure constant as a function of $x$ variable in the case of tagging the scattered electrons at BeamCal (left) and LumiCal (right) detectors planned for ILC (500 GeV). Distributions at generator (dots) and reconstruction (squares) levels are shown. The uncertainties marked on these plots are statistical only.

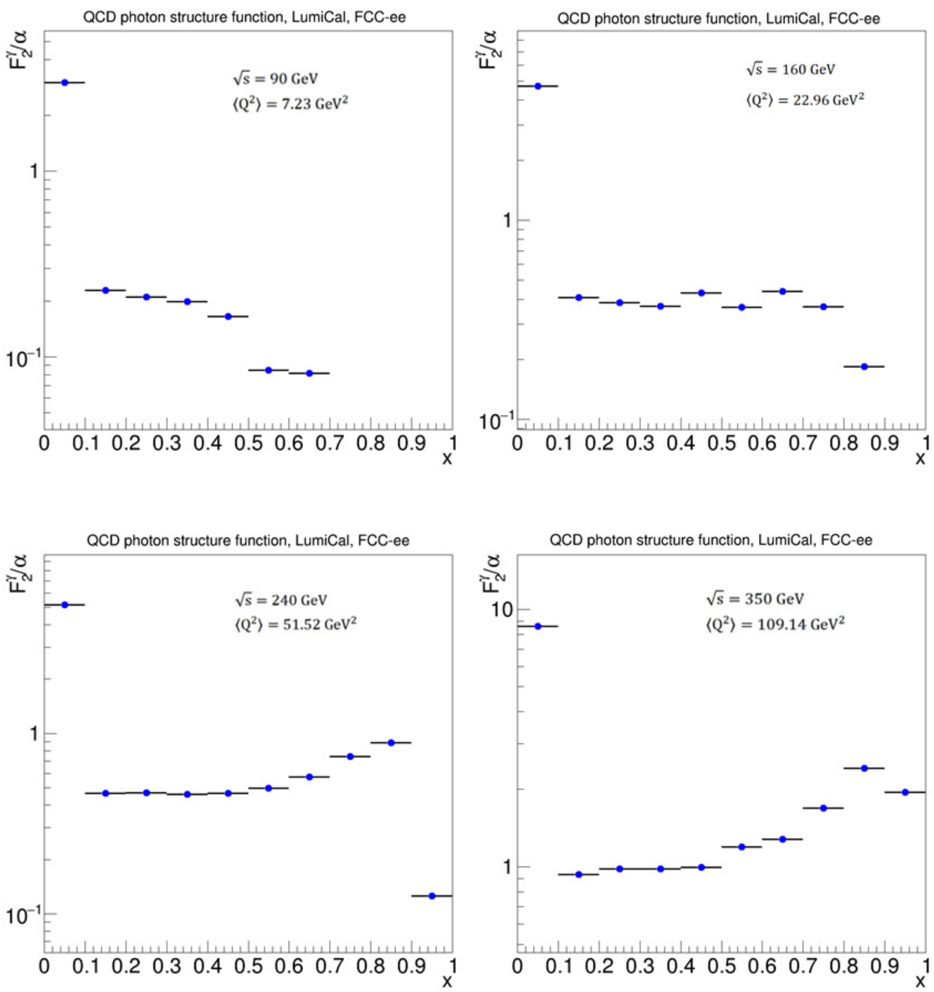


**Fig. 7:** The hadronic photon structure functions divided by the fine structure constant as a function of $x$ variable in the case of tagging the scattered electrons at LumiCal detector planned for FCC-ee. Generator-level distribution with negligible statistical uncertainties.

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