The gluon content of the photon from di-jet production at the $\gamma\gamma$-collider

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Abstract

A study of di-jet measurements at a future photon-photon collider is reported. The sensitivity to extract the gluon distribution is discussed. The results are compared with calculations for a linear $e^+e^-$ collider.

Key words: di-jets; Photon-Photon collider, gluon density in the photon

1 Introduction

A future linear $e^+e^-$ collider in the few hundred GeV centre of mass (CMS) energy range, offers the opportunity for a high energy $\gamma\gamma$-collider, i.e. collisions of high energy photon beams with a high luminosity. This can be achieved by Compton-backscattering of photons off a laser beam on the electron and positron beams of the $e^+e^-$ collider. Under the appropriate kinematical and geometrical conditions a narrow spectrum of high energy photons is produced, which can reach up to 80% of the original $e^+e^-$ beam energy.

The QCD process of two-photon jet production has a large cross section, thus the measurements will be dominated by systematics. Jets can be produced in hard partonic scattering in direct and resolved processes. For resolved processes the photon converts first into a hadron with vector meson quantum numbers, or splits into a quark-antiquark pair. The collision of two resolved photons is called a double resolved process. A photon can also couple directly to the quarks of the resolved second photon (called single resolved process), or to another bare photon via a quark loop (called direct process). Examples of these processes are shown in Fig. 1.

The resolved processes involve the hadronic component from one or both photons and are thus sensitive to the hadronic structure of the photon. Measurements of the hadronic structure of the photon have been made in $e\gamma$ scattering.
at $e^+e^-$ colliders over the last 20 years (2). These measurements are predominantly sensitive to the quark content of the photon, although they also start to constrain the gluon content of the photon via scaling violations at low values of $x_\gamma$. Measurements of jet cross sections on the other hand are directly sensitive to both the quark and gluon content of the photon and can thus, in combination with results from $e\gamma$ scattering, be used to measure the gluon distribution in the photon. Recently studies of di-jet events in $\gamma\gamma$ interactions at LEP (3; 4) and $\gamma p$ photoproduction interactions at HERA (5) have shown a direct sensitivity to the gluon distribution in the photon.

In this paper a study is presented of di-jet cross sections at a photon collider (PC), and the sensitivity to the structure of the photon is investigated. The results are compared with expectations for a linear $e^+e^-$ collider.

![Leading Order production diagrams](image)

Fig. 1. Examples of Leading Order production diagrams (from top to bottom): direct, single resolved and double resolved processes.

## 2 Monte Carlo Study

The study is made with the Monte Carlo Generator program PHOJET (version 1.12) (6) which contains all leading order (LO) diagrams complemented by parton showers to emulate higher order contributions. Hadronization of the parton final state is provided by the JETSET (7) program. The transverse energy of the jets provides a hard scale which regularizes perturbative QCD calculations. Jets are reconstructed using the inclusive $k_\perp$ clustering algorithm as proposed in (8). In this algorithm the distance measure between any pair of objects $\{i, j\}$ to be clustered is taken to be $d_{ij} = \min \left( E_{T,i}^2, E_{T,j}^2 \right) \left( R_{i,j}^2 / R_0^2 \right)$
with \( R^2_{ij} = (\Delta \eta_{ij})^2 + (\Delta \phi_{ij})^2 \). Throughout this analysis we set \( R^2_0 = 1 \). \( E_{T,i} \), \( \eta_i \), and \( \phi_i \) are the transverse energy, pseudorapidity, and azimuthal angle of the \( i \)-th object in the laboratory center-of-mass system. The transverse energy \( E_{T,i} \) of an object \( i \) is defined relative to the \( z \) axis of the detector. The clustering starts from the smallest value \( d_{\text{min}} \) of the combined set of all \( d_{ij} \) and all \( d_i = E_{T,i}^2 \). If \( d_{\text{min}} \) belongs to the subset \( d_{ij} \), the two objects \( i \) and \( j \) are merged into a new object using the \( E_T \) recombination scheme. In this scheme the properties of the merged particle are computed as
\[
E_{T} = E_{T,i} + E_{T,j},
\]
\[
\eta' = (E_{T,i} \eta_i + E_{T,j} \eta_j) / E_{T}',
\]
and
\[
\phi' = (E_{T,i} \phi_i + E_{T,j} \phi_j) / E_{T}'.
\]
If \( d_{\text{min}} \) belongs to the subset \( d_i \), the object is added to the list of jets and removed from the clustering list. The procedure is finished when no objects are left in the clustering list.

Realistic detector cuts, imposed by the TESLA detector study group (9) are applied in the Monte Carlo study. Unless otherwise specified jets are required to have a pseudorapidity \( \eta \) in the range \(|\eta| < 2.5\).

The kinematics of the two jets is used to estimate the fraction of the photon momentum participating in the interaction, \( x_\gamma \), which is a sensitive probe of the structure of the photon. A variable, defined at the hadronic final state, is
\[
x_{\gamma}^\pm = \frac{\Sigma_{\text{jets}}(E \pm p_z)}{\Sigma_{\text{hadrons}}(E \pm p_z)}
\]
and is closely related to the true partonic \( x_\gamma \) variable. Here \( E \) and \( p_z \) denote the energy and longitudinal momentum respectively. Direct processes are characterized by having a \( x_\gamma \) value close to one.

A linear e\(^+\)e\(^-\) collider with a CMS energy of 500 GeV is assumed. The expected luminosity of TESLA is 200 fb\(^{-1}\)/year, and for the photon collider about 10 times lower (for the high energy part of the photon spectrum).

### 3 Results

Fig. 2 shows the di-jet cross section for a photon collider, as a function of \( E_T \) of the jets and the average \( \eta \) of the jet pair. The \( x_\gamma \) distribution is shown as function of minimum \( E_T \) thresholds for the jets (each event gives two entries: \( x_{\gamma}^+ \) and \( x_{\gamma}^- \)). E.g. the entry 5/3 GeV means that the first jet has an \( E_T \) above 5 GeV, while the second jet has an \( E_T \) above 3 GeV. Clearly lower thresholds allow to reach lowest \( x_\gamma \) values, which are of particular interest. In this region the gluon induced processes are anticipated to dominate, and moreover a strong rise of the gluon density is predicted at small \( x \) from models mirrored to the evolution dynamics of proton parton densities. For the photon such a rise at small \( x \) has not been unambiguously observed yet. The proposed
measurements reach an order of magnitude further down in $x_\gamma$ compared to current measurements from jets at LEP and HERA [3, 4, 5].

It is important to note that also for the highest $E_T$ cuts studied there is still a good sensitivity to parton densities at low $x$. The final choice of the $E_T$ thresholds will depend on the acceptance and background conditions and on the control of theoretical uncertainties, such as underlying event effects, which may spoil the extraction of the gluon distribution from the data. Generally the cuts are expected to be in the range given in this figure. The cross sections for all threshold combinations are large, hence the measurement of these processes will be systematics dominated. Unless stated differently, the results below are for the $(5/3)$ GeV threshold pair, which is presently used in jet studies at LEP.

Fig. 3(a,b) shows the effect from the restricted $\eta$ range for jet measurements in a future detector on the low-$x$ reach of $x_\gamma$. The effect is large, and better $\eta$ coverage will allow to reach smaller values in $x_\gamma$. 

Fig. 2. The di-jet cross section as a function of $E_T$ and $\eta^{\text{jet}}_{\text{mean}} = (\eta^{\text{jet}1} + \eta^{\text{jet}2})/2$ and $x_\gamma$. The latter is shown on a linear and logarithmic scale, and for increasing thresholds of the jet transverse energy.
Fig. 3. The effect of the $\eta$-acceptance on the reach in $x_\gamma$ (a,b). (c) shows the di-jet cross section as a function of $x_\gamma$ for two different parton distribution functions, GRV and SaS. In (d) the ratio of the cross sections is shown.

Fig.3(c,d) show the sensitivity of the cross section as a function of $x_\gamma$ to two different parton distributions for the photon, GRV LO (10) and SAS 1D (11), which are both consistent with present day measurements of the photon structure. At low $x$ the differences in cross section are as large as a factor two, well within the sensitivity expected of the measurement.

In Fig.4(a,b) the contribution of gluon induced processes, compared to all processes, is shown for (7/5) GeV $E_T$ thresholds. A small smeared peak from direct contributions is seen close to $x_\gamma =1$. However in most of the region the processes are dominated by parton scattering involving gluons, and thus sensitive to the gluon distribution in the photon. At small $x_\gamma$ the gluon contribution amounts to 90%.

Fig. 4(c,d) shows the same distributions but for an $e^+e^-$ collider, where two photon interactions result from photons emitted from the beam leptons de-
Fig. 4. The contribution of gluon initiated processes to the di-jet cross section as a function of $x_\gamma$. The case of the $\gamma\gamma$-collider in the upper plots is compared to the $e^+e^-$-option in the lower plots. On the left hand side the relative contributions are shown.

scribed by a Weizäcker-Williams energy distribution. Hence the energy of the photons is in general much smaller than that of the photons from a photon collider, based on the same $e^+e^-$ machine. The cross sections at an $e^+e^-$ collider are much smaller, thus loosing the benefit of a higher luminosity. Furthermore, the quark induced processes have relative larger contributions at an $e^+e^-$ collider, blurring the extraction of the gluon distribution from the jet measurement much more than in the photon collider case.

4 Summary

Di-jet production at a future photon collider has been studied, including restrictions imposed by a possible detector, and discussed in terms of the $x_\gamma$. 
variable which is a measure of the hadronic structure of the photon. With presently anticipated experimental restrictions, values of $x_\gamma$ down to a few times $10^{-3}$ can be reached. At low $x_\gamma$ the cross section is predicted to be dominated by the gluon content of the photon, and can thus be used to extract the gluon distribution. The photon collider has several advantages, such as large cross sections and better dominance of gluon induced processes, over a $e^+e^-$ collider.

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