Results from $\gamma\gamma$ collisions in OPAL*

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Abstract. The production of charged hadrons and jets is measured in collisions of quasi-real photons. The data were taken with the OPAL detector at LEP at $e^+e^-$ centre-of-mass energies $\sqrt{s_{ee}} = 161$ and 172 GeV. The measured cross-sections are compared to perturbative next-to-leading order QCD calculations. The separation of the direct and the resolved component of the photon is demonstrated.

INTRODUCTION

In an $e^+e^-$ collider both beam electrons can radiate virtual photons which interact with each other. These photons are described by their negative four-momentum transfer $Q^2$ which is usually small ($Q^2 \approx 0$). They can therefore be considered to be quasi-real. Accordingly the beam electrons are scattered with very small angles and are not detected (anti-tagged). Events where one or both scattered electrons are detected are called single-tagged or double-tagged [1].

The interactions of the photons can be modelled by assuming that each photon can either interact directly or appear resolved through its fluctuations into hadronic states. In leading order Quantum Chromodynamics (QCD) this model leads to three different event classes for $\gamma\gamma$ interactions: direct, single-resolved and double-resolved. In resolved events the partons (quarks or gluons) inside the photon take part in the hard interaction. The probability to find partons inside the photon is parametrised by parton density functions. Due to the direct photon interactions the transverse momentum distribution of the charged hadrons in two-photon interactions is expected to have a harder component than in photon-proton or hadron-proton interactions. This is demonstrated by comparing the $\gamma\gamma$ data to photo- and hadroproduction data measured by WA69 [2].

Events with two jets (dijet events) offer the possibility to separate direct and resolved processes. The jet cross-sections can be compared to QCD calculations using different structure function parametrisations. Resolved processes are especially sensitive to the gluon content of the photon.

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HADRON PRODUCTION IN $\gamma\gamma$ EVENTS

We present the first measurement of inclusive charged hadron production in anti-tagged $\gamma\gamma$ collisions. The data were taken in 1996 and correspond to an integrated luminosity of 20 pb$^{-1}$.

To select anti-tagged two-photon events a set of cuts is applied to the data, the most important cuts are: The visible invariant hadronic mass $W_{\text{ECAL}}$ measured in the electromagnetic calorimeter has to be greater than 3 GeV, to reject multihadronic events the sum of all energy deposits in the electromagnetic and hadronic calorimeters should be less than 45 GeV and at least 3 tracks must have been found in the tracking chambers which rejects lepton pair events. To select only anti-tagged events there is a cut on the maximum energy deposit in the forward and silicon tungsten calorimeters that are located at small angles. After applying the whole set of cuts around 59000 events remain. Fig. 1 shows the differential cross-section $d\sigma/dp_T$ as a function of the transverse momentum $p_T$ of the hadrons. The data are compared with results from $\gamma p$ and $hp$ scattering ($h=\pi,K$) from the WA69 experiment which have been normalised to the $\gamma\gamma$ data. At $p_T > 2$ GeV/c the data lie significantly above the exponentially falling $\gamma p$ and $hp$ data due to the contribution from the direct $\gamma\gamma$ interactions. The $\gamma\gamma$ data are also compared to next-to-leading order (NLO) calculations [3] containing the three components of the direct, single-resolved and double-resolved processes. The calculations show clearly the dominance of the direct component at large transverse momenta. Most hadrons have small transverse momenta, in a regime where the resolved component dominates. This means that in most cases the photon behaves like a hadron.

**FIGURE 1.** The distribution measured in $\gamma\gamma$ interactions is compared to the $p_T$ distribution measured in $\gamma p$ and $hp$ ($h=\pi,K$) interactions in WA69.
JET PRODUCTION IN $\gamma\gamma$ EVENTS

The same data and a similar set of cuts as in the charged hadron analysis are used to investigate the production of jets in anti-tagged $\gamma\gamma$ interactions [4]. To select jets a cone jet finding algorithm is applied to the data requiring a minimum transverse energy of the jets of $E_{T}^{\text{jet}}>3$ GeV, the pseudorapidity $|\eta^{\text{jet}}|$ to be less than 2 and the cone size $R$ to be equal to 1. Especially events where two jets are found offer the possibility to differentiate between direct and resolved interactions [5]. A pair of variables, $x_{+}^{\gamma}$ and $x_{-}^{\gamma}$, can be defined which is a measure of the photon’s energy participating in the hard interaction:

$$x_{\pm}^{\gamma} = \frac{\sum_{\text{jets}}(E \pm p_{z})}{\sum_{\text{had}}(E \pm p_{z})},$$

where $p_{z}$ is the momentum component along the $z$ axis of the detector and $E$ is the energy of the jets or hadrons. In direct events the whole energy is concentrated in the two jets whereas in resolved events there is also energy outside the two jet cones due to the remnant of the resolved photon(s). So events with $x_{+}^{\gamma} > 0.8$ mainly stem from direct and events with $x_{+}^{\gamma} < 0.8$ mainly from resolved processes.

In direct events quark exchange dominates the interaction, whereas gluon exchange dominates in resolved events. This gives rise to different angular distributions which can be seen in Fig. 2. The parton (jet) scattering angle $|\cos \theta^{*}|$ in the centre-of-mass system of the outgoing partons (jets) is plotted. The two components are well separated, in the data as well as in the calculations. The right plot in Fig. 2 shows the inclusive two-jet cross-section as a function of $E_{T}^{\text{jet}}$ for jets with $|\eta^{\text{jet}}| < 2$ compared to NLO calculations by Kleinwort and Kramer [6]. The agreement between the data and the calculations is good apart from the lowest $E_{T}^{\text{jet}}$ bin.

Especially double-resolved events are sensitive to the gluon content of the photon described by different parton density functions. This leads to different predictions of the inclusive two-photon cross-section. Fig. 3 shows the inclusive two-photon cross-section.

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**FIGURE 2.** Angular distribution of events with large direct and large double-resolved components according to the separation with $x_{+}^{\gamma}$ and $x_{-}^{\gamma}$. The right plot shows the inclusive two-jet cross-section as a function of $E_{T}^{\text{jet}}$. 

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two-photon cross-section as a function of $|\eta^{\text{jet}}|$ for double-resolved events ($x^{\pm}_\gamma < 0.8$) in comparison with Monte Carlo models with different photon structure functions. The LAC1 parametrisation [7] overestimates the inclusive two-jet cross-section significantly.

![Graph](image)

**FIGURE 3.** The inclusive two-jet cross-section as a function of $|\eta^{\text{jet}}|$ for jets with $E^{\text{jet}}_T > 3$ GeV for events with a large contribution of double-resolved events (requiring $x^{\pm}_\gamma < 0.8$).

**CONCLUSION**

The differential cross-section $d\sigma/dp_T$ of charged hadrons in $\gamma\gamma$ events was found to have a harder component than in $\gamma p$ or $h p$ scattering due to the presence of the direct photon-quark coupling. The NLO calculations confirm the higher cross-section at large transverse momenta.

Events with two jets were identified using a cone jet algorithm. A pair of variables $x^+_\gamma$ and $x^-_\gamma$ is used to separate experimentally the events emerging from direct and resolved interactions. Both components are well separated in the distribution of the parton (jet) scattering angle $|\cos \theta^*|$. The agreement between the data and the NLO calculations is good.

**REFERENCES**

4. OPAL Collaboration, paper LP-201 submitted to the Lepton Photon Symposium 1997, Hamburg, Germany.