FINAL STATES IN $\gamma\gamma$ AND $\gamma p$ INTERACTIONS *

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The total hadronic $\gamma\gamma$ cross-section measured by L3 and OPAL and the apparent discrepancy between the results are discussed. OPAL measurements of jet and charged hadron production in $\gamma\gamma$ scattering and preliminary H1 results on $\pi^0$ production in $\gamma p$ scattering are also presented. The mechanism of baryon number transfer in $\gamma p$ interactions at HERA has been studied for the first time by H1.

1 Total Hadronic $\gamma\gamma$ Cross-Section

At high $\gamma\gamma$ centre-of-mass energies $W = \sqrt{s_{\gamma\gamma}}$, the total hadronic cross-section $\sigma_{\gamma\gamma}$ for the production of hadrons in the interaction of two real photons is expected to be dominated by interactions where the photon has fluctuated into a hadronic state. Measuring the $W$ dependence of $\sigma_{\gamma\gamma}$ should therefore improve our understanding of the hadronic nature of the photon and the universal high energy behaviour of total hadronic cross-sections.

Before LEP2 the energy dependence of $\sigma_{\gamma\gamma}(W)$ had only been measured in the low energy region $W < 20$ GeV. These energies are too low to observe the high energy rise which is typical for hadronic cross-sections. Using the LEP2 data, L3 and OPAL have now measured $\sigma_{\gamma\gamma}(W)$ in the ranges $5 \leq W \leq 145$ GeV and $10 \leq W \leq 110$ GeV, respectively. The results are shown in Fig. 1.

Before interpreting these results, the apparent discrepancy between the OPAL and L3 measurements and the interpretation of the systematic errors require some discussion. OPAL shows the average of the results obtained by determining the detector corrections using either the Monte Carlo model PHOJET or PYTHIA and takes the difference between these results as part of the systematic error. L3 uses PHOJET to determine the central values and gives no model dependent systematic error. For $W < 20$ GeV the systematic errors become large in the case of L3 due to the finite trigger acceptance. OPAL avoids these regions by applying harder selection cuts. It should also be noted that the errors are highly correlated within one experiment. In order to make the two experiments more comparable, the L3 results for $\sqrt{s_{ee}} = 183$ GeV obtained with the PYTHIA and PHOJET simulation of the detector, separately, are averaged in Fig. 2 and the full range is shown as vertical error bar. Comparing these results with the OPAL measurement shows that no significant discrepancy ex-

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The interaction of quasi-real photons ($Q^2 \approx 0$) studied at LEP and the interaction of a quasi-real photon with a proton studied at HERA (photoproduction) are very similar processes. In leading order (LO) different event classes can be defined in $\gamma \gamma$ and $\gamma p$ interactions. The photons can either interact as ‘bare’ photons (“direct”) or as hadronic fluctuation (“resolved”). Direct and resolved interactions can be separated by measuring the fraction $x_\gamma$ of the photon’s momentum participating in the hard interaction for the two photons. In $\gamma \gamma$ interactions they are labelled $x_\gamma^+$ for the two photons. Ideally, the direct $\gamma \gamma$ events with two bare photons are expected to have $x_\gamma^+ = 1$ and $x_\gamma^- = 1$, whereas for double-resolved events both values $x_\gamma^+$ and $x_\gamma^-$ are expected to be much smaller than one. In photoproduction, the interaction of a bare photon with the proton is labelled ‘direct’ (corresponding to the ‘single resolved’ process in $\gamma \gamma$) and the interaction of a hadronic photon is called ‘resolved’ (corresponding to ‘double-resolved’ in $\gamma \gamma$).
3 Di-Jet Production in $\gamma\gamma$ Interactions

Studying jets should give access to the parton dynamics of $\gamma\gamma$ and $\gamma p$ interactions. OPAL has therefore measured di-jet production in $\gamma\gamma$ scattering at $\sqrt{s_{\text{ee}}} = 161 - 172$ GeV using the cone jet finding algorithm with $R = 1$. Similar studies have been presented by the HERA experiments. In di-jet events, $x_\gamma^\pm$ is calculated using

$$x_\gamma^+ = \frac{\sum_{\text{jets}=1,2} (E + p_z)}{\sum_{\text{hadrons}} (E + p_z)} \quad \text{and} \quad x_\gamma^- = \frac{\sum_{\text{jets}=1,2} (E - p_z)}{\sum_{\text{hadrons}} (E - p_z)},$$

(3)

where $p_z$ is the momentum component along the $z$ axis of the detector and $E$ is the energy of the jets or hadrons.

For a given jet-jet centre-of-mass energy the cross-sections vary only with the scattering angle $\theta^*$. The leading order direct process $\gamma\gamma \rightarrow q\bar{q}$ is mediated by $t$-channel spin-$\frac{1}{2}$ quark exchange which leads to an angular dependence $\propto (1 - |\cos \theta^*|^2)^{-1}$. In double-resolved processes all matrix elements involving quarks and gluons have to be taken into account, with a large contribution from spin-0 gluon exchange. After adding up all relevant processes, perturbative QCD predicts an angular dependence of approximately $\propto (1 - |\cos \theta^*|^2)^{-2}$. Fig. 3 shows the corrected $|\cos \theta^*|$ distribution of di-jet events with $x_\gamma^+ > 0.8$ and with $x_\gamma^+ < 0.8$ compared to a NLO calculation which qualitatively reproduces the data.

The transverse momentum $E_T^{\text{jet}}$ of the jet (or the final-state parton) defines a hard scale which can be used together with $x_\gamma$ to constrain the parton densities $f(x_\gamma, E_T^{\text{jet}})$ of the photon. In the kinematic range covered by LEP the $E_T^{\text{jet}}$ measurements are mainly probing the quark content of the photon whereas di-jet production can be used to constrain the relatively unknown gluon distribution in the photon.

The $E_T^{\text{jet}}$ distribution for di-jet events with pseudo-rapacities $|\eta^{\text{jet}}| < 2$ is shown in Fig. 4. The measurements are compared to a NLO calculation which uses the NLO GRV parametrisation. The direct, single- and double-resolved parts and their sum are shown separately. The data points are in good agreement with the calculation except in the first bin where theoretical and experimental uncertainties are large.

![Figure 4: Angular distribution of di-jet events compared to NLO QCD calculations using the GRV parametrisation. The curves are normalised to the data in the first three bins. The invariant mass of the two-jet system must be larger than 12 GeV.](image)

![Figure 5: The inclusive $e^+e^-$ di-jet cross-section as a function of $E_T^{\text{jet}}$ for jets with $|\eta^{\text{jet}}| < 2$ using a cone size $R = 1$.](image)

The $x_\gamma$ distribution is shown in Fig. 5 in bins of $E_T^{\text{jet}}$, where $E_T^{\text{jet}}$ is the mean value of the transverse energies of the two jets. No detector correction has been applied. The Monte Carlo predictions of PYTHIA and PHOJET are normalised to the number of data events. The contribution from direct processes, as predicted from PYTHIA, is also shown. The events from direct processes are concentrated at high $x_\gamma$ values. As $E_T^{\text{jet}}$ increases, the $x_\gamma$ distribution shifts to higher values and the fraction of direct events in the PYTHIA sample increases. The number of events is underestimated by PYTHIA and PHOJET by about $25 - 30\%$, if the predicted Monte Carlo cross-sections are taken into account, mainly for $x_\gamma < 0.9$.

The NLO QCD calculations do not take into account the possibility of an underlying event which leads to an increased jet cross-section. The underlying event is simulated in the Monte Carlo models PYTHIA and PHOJET which will be used to compare to different LO parametrisations of the parton distribution, GRV, SaS-1D and LAC1. In PYTHIA and PHOJET the modelling of the underlying event includes multiple interactions. A resolved photon contains several partons which can lead to multiple parton interactions in double-resolved events.

The contribution from multiple interactions has to be tuned using quantities which are not directly correlated to the jets, since otherwise effects of the parton distributions and of the underlying event cannot be dis-
It is expected that the transverse energy flow outside the jets measured as a function of $x_{\gamma}$ is correlated to the underlying event. No effect due to the underlying event is expected for direct events at large $x_{\gamma}$. The increase of the transverse energy flow outside the two jets at small $x_{\gamma}$ can therefore be used to tune the number of multiple interactions in the model.

The events were boosted into their centre-of-mass system and the transverse energy flow was measured as a function of $x_{\gamma}$ in the central rapidity region $|\eta^\gamma| < 1$. The regions around the jet axes with $R < 1.3$ are excluded from the energy sum. Fig. 7 shows the transverse energy flows corrected to the hadron level compared to the Monte Carlo models with different values of the parameter $p_T^{\text{mi}}$ which defines the transverse momentum cutoff for multiple parton interactions. The following conclusions can be drawn:

- The influence of multiple interactions is small. The modelling of the transverse energy flow without multiple interactions is also consistent with the data.
- The optimised value of $p_T^{\text{mi}}$ depends on the parametrisation used for the parton distributions. For all further comparisons with PYTHIA, the cut-off parameter $p_T^{\text{mi}}$ was set to 2.5 GeV/c for LAC1, to 2.0 GeV/c for GRV and to 1.4 GeV/c for SaS-1D.

- PHOJET with either SaS-1D or GRV is in reasonable agreement with the data. Changing the default cutoff from $p_T^{\text{mi}} = 2.5$ GeV/c does not affect the transverse energy flow significantly.

- For $\gamma p$ collisions at HERA, $p_T^{\text{mi}} = 1.2$ GeV/c is the optimal choice with PYTHIA-GRV and $p_T^{\text{mi}} = 2.0$ GeV/c with PYTHIA-LAC1. With these values the models slightly overestimate the transverse energy flows at low $x_{\gamma}$ in the $\gamma\gamma$ data.

After this optimisation of the description of the underlying event by the generators, the sensitivity of the jet cross-sections to the choice of parametrisation for the

![Figure 6: Uncorrected $x_{\gamma}$ distribution in bins of the mean value of $E_T^{\text{jet1}}$ for di-jet events with $E_T^{\text{jet1}} > 3$ GeV and $|\eta^{\text{jet1}}| < 2$. Each event is added to the plot twice, at the values of $x_{\gamma1}$ and of $x_{\gamma2}$. Statistical errors only are shown.](image1)

![Figure 7: Transverse energy flow outside the jets in the central rapidity region $|\eta^\gamma| < 1$ as a function of $x_{\gamma}$. The statistical error is smaller than the symbol size. The error bars show the statistical and systematic errors added in quadrature. The data are compared with the MC models using a) LAC1 and b) GRV and SaS-1D.](image2)

![Figure 8: The inclusive two-jet cross-section as a function of $|\eta^{\text{jet1}}|$ for events with $E_T^{\text{jet1}} > 4$ GeV and $E_T^{\text{jet2}} > 3$ GeV is shown for events with a) $x_T^{\gamma1} < 0.8$ (mainly double resolved) and b) $x_T^{\gamma1} > 0.8$ (mainly direct). Asymmetric $E_T^{\text{jet1}}$ cuts were chosen to avoid singularities in the NLO calculations (not shown).](image3)
parton distributions can be studied. The inclusive di-jet cross-section as a function of $|\eta^{\gamma\gamma}|$ for events with a large double-resolved contribution obtained by requiring $x_T^+ < 0.8$ is shown in Fig. 3b. The larger gluon density in LAC1 compared to SaS-1D and GRV in the $(x_T, E_T^{\gamma\gamma})$ region probed here leads to an overestimation of the jet cross-section for double-resolved events. As expected, there exists almost no dependence on the choice of parametrisation for the mainly direct events with $x_T^- > 0.8$ in Fig. 3b.

4 Hadron Production in $\gamma\gamma$ and $\gamma p$ Scattering

Measurements of hadron production cross-sections in $\gamma\gamma$ and $\gamma p$ scattering complement the studies of jet production. Hadron production at large transverse momenta is sensitive to the partonic structure of the interactions without the theoretical and experimental problem related to the various jet algorithms. Interesting comparisons of $\gamma\gamma$ and $\gamma p$ data taken at LEP and HERA, respectively, should be possible in the future, since similar hadronic centre-of-mass energies $W$ of the order 100 GeV are accessible for both type of experiments.

4.1 Inclusive Charged Hadron Production in $\gamma\gamma$

The distributions of the transverse momentum $p_T$ of hadrons produced in $\gamma\gamma$ interactions are expected to be harder than in $\gamma p$ or hadron-p interactions due to the direct component. This is demonstrated in Fig. 3 by comparing $d\sigma/dp_T$ for charged hadrons measured in $\gamma\gamma$ interactions by OPAL to the $p_T$ distribution measured in $\gamma p$ and $hp$ ($h=\pi,K$) interactions by WA69. The WA69 data are normalised to the $\gamma\gamma$ data in the low $p_T$ region at $p_T \approx 200$ MeV/$c$ using the same factor for the $hp$ and the $\gamma p$ data. The hadronic invariant mass of the WA69 data is about $W = 16$ GeV which is of similar size as the average $\langle W \rangle$ of the $\gamma\gamma$ data in the range $10 < W < 30$ GeV.

Whereas only a small increase is observed in the $\gamma p$ data compared to the $h\pi$ data at large $p_T$, there is a significant increase of the relative rate in the range $p_T > 2$ GeV/$c$ for $\gamma\gamma$ interactions due to the direct process.

![Figure 10](image-url)  

**Figure 10:** $d\sigma/dp_T$ for pseudorapidities $|\eta| < 1.5$ in the range $10 < W < 125$ GeV compared to NLO calculations for $p_T > 1$ GeV/$c$ (continuous curve) together with the double-resolved (dot-dashed), single-resolved (dotted) and direct contributions (dashed).

The $\gamma\gamma$ data are also compared to a ZEUS measurement of charged particle production in $\gamma p$ events with a diffractively dissociated photon at $\langle W \rangle = 180$ GeV. The invariant mass relevant for this comparison should be the mass $M_X$ of the dissociated system (the invariant mass of the ‘$\gamma$-Pomeron’ system). The average $\langle M_X \rangle$ equals 10 GeV for the data shown. The $p_T$ distribution falls exponentially, similar to the $\gamma p$ and hadron-p data, and shows no flattening at high $p_T$ due to a possible hard component of the Pomeron.

The cross sections $d\sigma/dp_T$ are also compared to NLO calculations, which are calculated using the QCD partonic cross-sections, the NLO GRV parametrisation of the parton distribution functions and fragmentation functions fitted to $e^+e^-$ data. The renormalisation and factorisation scales are set equal to $p_T$. The change in slope around $p_T = 3$ GeV/$c$ in the NLO calculation is due to the charm threshold.

In Fig. 3 the NLO calculation is shown separately for direct, single- and double-resolved interactions. At large $p_T$ the direct interactions dominate. The agreement...
between the data and the NLO calculation is good.

4.2 Inclusive \( \pi^0 \) Production in \( \gamma p \)

H1 has studied \( \pi^0 \) production in photoproduction by reconstructing the \( \pi^0 \to \gamma\gamma \) decays using the new lead-scintillating fibre calorimeter SpaCal in the backward region (photon hemisphere). Fig. 11 shows the \( \pi^0 \) cross-section as a function of the rapidity \( y \) together with the model predictions of PHOJET and PYTHIA. PYTHIA gives a better description of the data than PHOJET. The accuracy of the data is, however, not yet sufficient to distinguish multiple interaction models.

The differential cross-section \( d\sigma/dp_T \) is presented in Fig. 12 together with H1 results on charged hadron production in the central pseudorapidity region (|\( \eta \)| < 1.5). Fitting an exponential and a power law function to the \( p_T \) spectrum shows that the low \( p_T \) region, \( p_T < 1.3 \) GeV, is well described by an exponential fall-off typical for soft hadronic interactions, but at high \( p_T \) a deviation is observed. In this region a power law function, which is typical for hard scattering processes, fits the data best.

5 Baryon-Antibaryon Asymmetry

It has been suggested by Kopeliovich and Povh that the Baryon Number (BN) of the proton in \( \gamma p \) scattering can either be carried by the valence quarks or by the sea quarks and gluons. The gluonic mechanism of BN transport proceeds through the production of baryon-antibaryon pairs in the photon fragmentation region.

H1 has studied this phenomenon in tagged photoproduction (150 < \( W \) < 260 GeV) by measuring the baryon-antibaryon asymmetry

\[
A_B = 2\frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}
\]

from the number of protons, \( N_p \), and antiprotons, \( N_{\bar{p}} \), per event. The theoretical expectation for the rapidity dependence of \( A_B \) is shown in Fig. 13.

![Figure 12](image-url)

Figure 12: \( d\sigma/dp_T \) for \( \pi^0 \) produced in \( \gamma p \) interactions. The triangles indicate the H1 result on charged hadrons in the central rapidity region. The curves are different fits to the data.

![Figure 13](image-url)

Figure 13: Baryon-antibaryon asymmetry \( A_B(\eta) \) as a function of rapidity \( \eta \) for photoproduction at HERA. The dashed line corresponds to the gluonic mechanism of BN transfer and the dotted line to the quark mechanism which is peaked in the forward direction. The sum is shown as continuous line.
the Central Jet Chamber is twice the energy loss expected for a minimum ionising particle. Additional cuts reduce the background from beam-gas interactions and from secondary protons produced in the beam pipe. The baryon-antibaryon asymmetry is measured to be

$$A_B = 0.8 \pm 1.0 \text{(stat)} \pm 2.5 \text{(sys)} \%$$

for (anti-)protons with momenta $0.3 < p < 0.6 \text{ GeV}/c$ and for polar angles $|\cos \theta| < 0.8$ ($|\eta| < 1.1$). The $\cos \theta$ dependence of $A_B$ is in qualitative agreement with the data in Fig. 14, yielding a non-vanishing asymmetry at about 7 rapidity units from the leading baryon production region. A quantitative comparison is not yet possible, since the (anti-)proton momentum cut and additional requirements on the multiplicity have not be applied in the model. In Fig. 14b, $A_B$ is shown as a function of the number of accompanying charged particles, $N_{\text{ch}}^{\text{obs}}$, within the same angular interval as the (anti-)protons. The increase of $A_B$ with $N_{\text{ch}}^{\text{obs}}$ is also in qualitative agreement with the expectation for the gluonic mechanism of BN transport.

6 Summary

The L3 and OPAL measurements of the total hadronic $\gamma\gamma$ cross-section are consistent. The measurements favour a stronger rise of the total cross-section with energy than observed in $\gamma p$, $pp$ or $p\bar{p}$ scattering.

The OPAL results on di-jet production in $\gamma\gamma$ scattering are well understood within the framework of perturbative NLO QCD. The di-jet cross-sections help to constrain the gluon content of the photon.

Comparisons of transverse momentum distributions measured in different processes yield information about the partonic structure of the interactions.

A first H1 measurement of a non-vanishing baryon asymmetry in the photon hemisphere is in qualitative agreement with the gluonic mechanism of baryon number transport.

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