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EXCLUSIVE PRODUCTION OF HADRON PAIRS AT LARGE MOMENTUM TRANSFER IN PHOTON–PHOTON INTERACTIONS

PLUTO Collaboration

Ch. BERGER, A. DEUTER, H. GENZEL, W. LACKAS, J. PIELORZ, F. RAUPACH, W. WAGNER
I. Physikalisches Institut der RWTH Aachen [1], *Federal Republic of Germany*

A. KLOVNING, E. LILLESTÖL, J.M. OLSEN
University of Bergen [2], *Norway*

J. BÜRGER [3], L. CRIEGEE, F. FERRAROTTO [4], G. FRANKE, M. GASPERO [4], Ch. GERKE [5], G. KNIES, B. LEWENDEL, J. MEYER, U. MICHELSEN, K.H. PAPE, B. STELLA [4], U. TIMM, G.G. WINTER, M. ZACHARA [6], W. ZIMMERMANN,
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Federal Republic of Germany

P.J. BUSSEY, S.L. CARTWRIGHT [7], J.B. DAINTON, B.T. KING, C. RAINE, J.M. SCARR, I.O. SKILLICORN, K.M. SMITH, J.C. THOMSON
University of Glasgow [8], *UK*

O. ACHTERBERG [9], V. BLOBEL, D. BURKART, K. DIEHLMANN, M. FEINDT, H. KAPITZA, B. KOPPITZ, M. KRÜGER [9], M. POPPE, H. SPITZER, R. van STAA,
II. Institut für Experimentalphysik der Universität Hamburg [7], *Federal Republic of Germany*

C.Y. CHANG, R.G. GLASSER, R.G. KELLOGG, S.J. MAXFIELD, R.O. POLVADO [10], B. SECHI-ZORN, J.A. SKARD, A. SKUJA, A.J. TYLKA, G.E. WELCH, G.T. ZORN
University of Maryland [11], *USA*

F. ALMEIDA [12], A. BÄCKER, F. BARREIRO, S. BRANDT, K. DERIKUM [13], C. GRUPEN, H.J. MEYER [5], H. MÜLLER, B. NEUMANN, M. ROST, K. STUPPERICH, G. ZECH
Universität-Gesamthochschule Siegen [1], *Federal Republic of Germany*

G. ALEXANDER, G. BELLA, Y. GNAT, J. GRUNHAUS
Tel-Aviv University [14], *Israel*

and

H.J. DAUM, H. JUNGE, K. KRASKI, C. MAXEINER, H. MAXEINER, H. MEYER and D. SCHMIDT
Universität-Gesamthochschule Wuppertal [1], *Federal Republic of Germany*

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[1] Supported by the BMFT, Federal Republic of Germany.

[2] Partially supported by Norwegian Council for Science and Humanities.

[3] Currently on leave of absence at CERN, Geneva, Switzerland.

[4] Rome University, partially supported by INFN, Sezione di Roma, Rome, Italy.

[5] Present address: CERN, Geneva, Switzerland.

[6] On leave from The Institute of Nuclear Physics, Cracow, Poland.

[7] Present address: Rutherford Appleton Laboratory, Chilton, England.

[8] Supported by the UK Science and Engineering Research Council.

[9] Present address: Universität Karlsruhe, Karlsruhe, Federal Republic of Germany.

[10] Present address: Northeastern University, Boston, MA, USA.

[11] Partially supported by the Department of Energy, USA.

[12] On leave of absence from Institute de Fisica, Universidad Federal do Rio de Janeiro, Brazil.

[13] Present address: BESSY, Berlin, Federal Republic of Germany.

[14] Partially supported by the Israeli Academy of Sciences and Humanities-Basic Research Foundation.

We report on the exclusive production of π, K and proton pairs from photon–photon interactions at momentum transfers $|t| \geqslant 1$ GeV^2. Using the PLUTO detector at the e^+e^- storage ring PETRA, we have observed 15 events in an integrated luminosity of 41.7 pb^{-1}. The data lie far below the expectations for point-like hadrons, and are in reasonable agreement with the QCD-based predictions of Brodsky and Lepage.

A topic of current interest in the study of two-photon interactions is the reaction

$$\gamma\gamma \to h^+h^- \qquad (1)$$

where h may be a π, K, or p. In the limit of large photon-to-hadron momentum transfer, t, the cross sections have been calculated for real photons in the framework of QCD [1,2]. These predictions are now directly comparable with data.

We have used interactions between quasi-real photons to measure this process in the reaction $e^+e^- \to e^+e^-h^+h^-$ (see fig. 1). In a previous study [3] we were able to determine only an upper bound on the cross section. In this paper, we present the first measurement of the above reaction at photon–photon center of mass energies above the main hadronic resonance region. A measurement of the sub-process, $\gamma\gamma \to p\bar{p}$, but at energies near the kinematic threshold, has been made by the TASSO collaboration [4].

Our data stem from an integrated luminosity of 41.7 pb^{-1} which was accumulated at PETRA between August 1981 and August 1982 at an average e^+e^- center-of-mass energy of 34.7 GeV. To study hadron pairs produced with large momentum transfer by quasi-real photons, we consider only events in which the scattered beam electrons remain in the beam-pipe, both hadrons appear at large lab angles, Θ_L, with respect to the beam axis ($|\cos\Theta_L| \leqslant 0.6$), and the momentum of each hadron in the photon–photon center of mass frame, p_{cm}, is at least 1 GeV/c. With these cuts the momentum transfer from the photons to the hadrons is $|t| \gtrsim 1$ GeV^2, and Θ^*, the angle between the photon and hadron directions in the photon–photon center of mass frame, is near 90°. The average value of $|\cos\Theta^*|$ is ~0.2. In this kinematic region we are unable to distinguish between π's, K's and p's. In fact we make no positive identification of the particles as hadrons, but require simply that they be non-leptons.

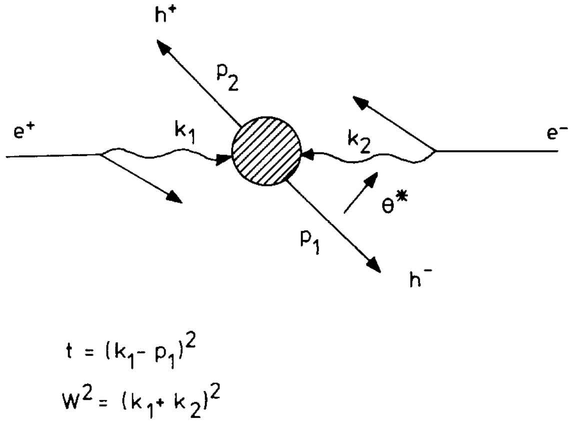

Fig. 1. A schematic diagram of the reaction $e^+e^- \to e^+e^-h^+h^-$.

The details of the PLUTO detector have been given elsewhere [5]. We briefly discuss here the relevant components. The final state particles are observed and their momenta measured by cylindrical proportional chambers in the solenoidal magnetic field of the central detector. Lepton identification is made using the muon chambers and the central (barrel) shower counters. The muon detector is composed of two separate sets of chambers: proportional chambers after approximately 70 cm of iron and drift chambers after an additional 30 cm of iron. The chambers cover approximately 85% of the angular region of this study. The barrel shower counter is a lead-scintillator shower counter with a total of 8.6 radiation lengths of material. These detector components allow us to make a reliable separation of electrons, muons, and hadrons at momenta larger than 900 MeV/c. In addition to the barrel shower counters, we use PLUTO's endcap and Large Angle Tagger (LAT) to reject events with extra photons and electrons. The resulting electromagnetic veto covers the complete angular region $|\cos\Theta_L| \leqq 0.996$.

We make the following cuts to reduce background, to ensure trigger efficiency, and to select a sample upon which we can make reliable lepton identification. Cosmic rays are removed by a time-of-flight cut and by the requirement that the intersection of each reconstructed track with the beam axis be within 40 mm of the beam crossing point. To reduce τ contamination, the neutral energy not associated with the charged particles is limited to 100 MeV. Muon pairs produced by e^+e^- annihilation are removed by requiring $p_{cm} \leqslant 5$ GeV/c. The two tracks are required to be coplanar within 6° to ensure uniform trigger efficiency, and each track must have a momentum of at least 0.9 GeV/c to permit efficient lepton–hadron separation. The requirements that no high energy electron be seen in the LAT or central detector shower counters, and that the net transverse momentum of the event be less than 0.5 GeV/c, ensure that the beam electrons are scattered at small angles. The average virtual photon mass squared is then -0.008 GeV^2.

At this stage about 2000 $\gamma\gamma \to$ two-prong exclusive events remain. More than 99% of the final states are leptonic. Since we identify hadrons only by requiring them to be neither electrons nor muons, unidentified $\gamma\gamma \to ee$ and $\gamma\gamma \to \mu\mu$ events are a potentially serious background. Lepton identification proceeds as follows.

Two-electron final states are removed by rejecting events in which at least one particle deposits either more than 500 MeV, or more than an energy equal to half of its momentum, in the barrel shower counter. The probability that a single electron fails to be identified by this criterion has been measured to be 0.017 ± 0.005. Since the identification of each prong is independent, the residual $\gamma\gamma \to ee$ contamination in the 987 events identified as not containing electrons is only 0.3 ± 0.2 event. Unfortunately, since hadrons occasionally interact in the shower counters, this cut also rejects approximately 30% of the $\gamma\gamma \to hh$ events.

To identify $\gamma\gamma \to \mu\mu$ events with sufficient efficiency, it is necessary to reject events in which the tracks point toward an area of iron absorber which is too thick for them to penetrate, or toward an area with poor μ-chamber coverage. For each event the probability that at least one of the tracks would hit a μ-chamber, if it were in fact a μ, is calculated. The distribution of this muon identification probability displays a sharp peak within a few tenths of a percent of 1.0. Only those events for which the probability is greater than 98% are retained.

This leaves 651 events, of which 16 do not contain an identified muon. The estimated residual contamination of unidentified muons is 0.9 events. Residual unidentified electrons represent 0.2 events, since one-third of the previously unidentified $\gamma\gamma \to ee$ events can be expected to fail the requirement on the muon identification probability. The background, including beam–gas interactions, from processes other than $\gamma\gamma \to h^+h^-$, ee, or $\mu\mu$ is estimated to be negligible. Thus we have 14.9 ± 4.0 $\gamma\gamma \to h^+h^-$ events. The number of hadron events incorrectly rejected as muons is calculated to be negligible. When we adjust for the hadrons which were incorrectly rejected as electrons, we obtain 21.7 ± 5.8 produced hadronic events. The average value of $|t|$ for these events is 2.1 ± 0.2 GeV^2. The average value of $|\cos \Theta^*|$ is 0.25 ± 0.04.

We have studied the reaction $\gamma\gamma \to \mu\mu$ in order to understand our muon detection efficiency and found its cross section consistent with QED. Because it provides a convenient calibration reaction, we express our results in terms of R_{hh}, the observed ratio of hadron to muon pairs,

$$R_{hh}(p_{cm}) = \frac{dN(e^+e^- \to e^+e^-h^+h^-)/dp_{cm}}{dN(e^+e^- \to e^+e^-\mu^+\mu^-)/dp_{cm}} . \qquad (2)$$

Fig. 2. shows R_{hh}, calculated for our entire angular acceptance, $|\cos \Theta_L| \leqslant 0.6$, as a function of p_{cm}. After correcting bin-by-bin for acceptance losses, a single value of R_{hh} for the momentum range $1 \leqslant p_{cm} \leqslant 5$ GeV/c can be calculated. We find

$$R_{hh} = 0.060 \pm 0.019\ (\text{stat.}) \pm 0.015\ (\text{syst.}) .$$

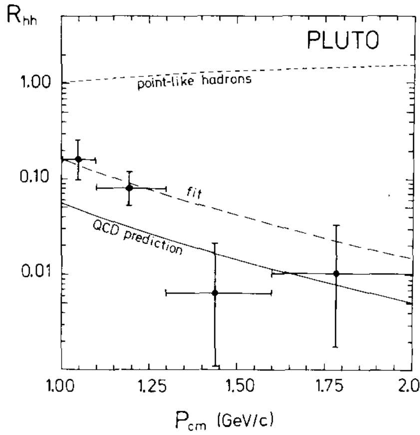

Fig. 2. Ratio of hadron to muon pairs: The observed ratio of $\gamma\gamma \to h^+h^-$ to $\gamma\gamma \to \mu^+\mu^-$ as a function of the final state particle momenta in their center of mass. Both particles are produced at $|\cos \theta_L| \leqslant 0.6$. The solid line is the QCD prediction for π's, K's and p's with $C = 0.4$ GeV^2 (see text). The dashed line is obtained by fitting the value C to the data. ($C = 0.68$ GeV^2.) The dotted line is the expectation for point-like π's, K's and p's. (Error bars are statistical only.)

The quantity R_{hh} is a directly measured experimental quantity, which has the disadvantage of being tied to our specific acceptance, but is at least free of any dependence on assumptions concerning the hadron masses or angular distribution. Although in principle the calculation of p_{cm} (and hence R_{hh}) from the measured laboratory momenta depends on the mass of the hadrons, the magnitude of the effect is insignificant everywhere within our acceptance.

To provide a result more easily comparable to theoretical predictions, we calculate the photon–photon to hadron pair cross section at 90° in the center of mass, which is plotted as a function of p_{cm} in fig. 3. In calculating this cross section, however, it is necessary to introduce assumptions about the hadron masses, which we do not measure, and the angular distribution, which we measure only poorly. For the sake of comparison with the QCD calculations to be discussed below, we assume a p_{cm}-independent composition $\pi:\mathrm{K}:\mathrm{p} = 50:50:0$ and an angular distribution in $\cos\Theta^*$ identical to that of muons. Assuming a 100% K or π composition would move the data points in fig. 3 by at most ±10%. Protons, however, can create larger uncertainties. If the hadron composition were 100% protons, the data point at $p_{\mathrm{cm}} = 1.05$ GeV/c, where the effects are largest, would increase by a factor of 1.75. If the hadron distribution were flat in $\cos\Theta^*$, an assumption still consistent with our limited statistics, rather than the $(1+\cos^2\Theta^*)/(1-\cos^2\Theta^*)$ distribution characteristic of muons, all the data points in fig. 3 would increase by a factor of 1.5.

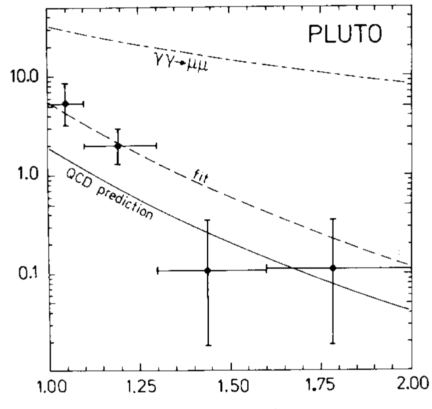

Fig. 3. The cross section $\mathrm{d}\sigma_{\gamma\gamma\to\mathrm{hh}}/\mathrm{d}\cos\theta^*$ at $\cos\theta^* = 0$ versus p_{cm}: The solid line is the QCD prediction for π's, K's and p's with $C = 0.4$ GeV^2 (see text). The dashed line is obtained by fitting the value of C to the data. ($C = 0.68$ GeV^2.) The dashed–dotted line is the $\gamma\gamma\to\mu\mu$ cross section at $\cos\theta^* = 0$ for comparison. (Error bars are statistical only. Systematic errors are discussed in the text.)

The two-photon production of point-like hadrons has been calculated in QED [6]. The dashed line in fig. 2 indicates these Born-term expectations for the sum of π's, K's and p's. They exceed the data by well over a factor of ten, confirming that at momentum transfer of $|t| \sim 2$ GeV^2 the effects of hadronic structure make themselves apparent.

In the framework of QCD, Brodsky and Lepage have calculated the differential cross section $\mathrm{d}\sigma/\mathrm{d}t$ for the two-photon production of meson pairs [1]. Using a similar technique, Damgaard has calculated the two-photon production of baryon pairs [2]. Since the calculations are similar in method, we briefly describe only the calculation of Brodsky and Lepage.

The production amplitude of $\gamma\gamma\to\mathrm{M\bar{M}}$ factorizes into two parts, a parton distribution amplitude and a hard scattering amplitude. The hard scattering amplitude is calculated in first-order QCD. The parton distribution amplitude, which cannot be calculated in perturbation theory, is related to the pion form factor in order to normalize the cross section. The cross section is then written

$$\mathrm{d}\sigma/\mathrm{d}t = (2/W^2)\,\mathrm{d}\sigma/\mathrm{d}\cos\Theta^*$$

$$= 16\pi\alpha^2\,[|F_{\mathrm{m}}(W^2)|^2/W^4]\,g(\Theta^*)\,, \qquad (3)$$

where $F_{\mathrm{m}}(W^2)$ is the meson electromagnetic form factor. For charged mesons, the function $g(\Theta^*)$ yields an angular dependence which is very similar to that of $\gamma\gamma\to\mu\mu$ and depends only weakly on the form of the parton distribution amplitude.

The mesons relevant to our measurements are charged π's and K's. Assuming that the parton wave functions exhibit flavor symmetry. Brodsky and Lepage show that $F_{\mathrm{m}}(W^2)$ should be directly proportional to f_{m}^2, the leptonic meson decay constant. The values of f_π and f_{K}, which are known to a few percent, indicate that $\mathrm{d}\sigma(\gamma\gamma\to\mathrm{K}^+\mathrm{K}^-)$ should be 2.1 times larger than $\mathrm{d}\sigma(\gamma\gamma\to\pi^+\pi^-)$ at the same W. At the same value of p_{cm}, however, W_{KK}, the invariant mass of a kaon pair, is larger than $W_{\pi\pi}$. The steep W-dependence of the cross sections then suppresses the kaon contribution with respect to the pions, particularly at small values of p_{cm}. For example, at $p_{\mathrm{cm}} = 1$ GeV/c the QCD prediction indicates that the observed ratio of kaons to pions should be 0.85. Overall, the QCD prediction indicates that the number of K's and π's in our sample should be about equal. Such mass effects also contribute to the suppression of proton–antiproton final states. In fact, using the QCD calculation of Damgaard [2] to extrapolate the TASSO [4] measurement of $\mathrm{p\bar{p}}$ production near threshold, we find that the expected number of $\mathrm{p\bar{p}}$ events in our sample is about 0.5.

Brodsky and Lepage [1] take the pion form factor to be

$$F_\pi(W^2) = C/W^2\,, \tag{4}$$

with $C = 0.4\ \mathrm{GeV}^2$. The QCD prediction for the sum of π's, K's and p's, using this value of C, is shown as the solid line in figs. 2 and 3. It lies somewhat below our measurements. A quantitative comparison can be made by letting the value of C in eq. (4) be a free parameter. Our observed number of events then corresponds to

$$C = 0.68 \pm 0.11\ (\mathrm{stat.}) \pm 0.08\ (\mathrm{syst.})\ \mathrm{GeV}^2.$$

The resulting fitted curve is shown as the dashed line in figs. 2 and 3.

In conclusion, we have measured the reaction $\mathrm{e^+e^-} \to \mathrm{e^+e^-h^+h^-}$ at momentum transfers of about $2\ \mathrm{GeV}^2$. The data lie an order of magnitude below the expectations for point-like hadrons, and are in reasonable agreement with the predictions of a QCD-based calculation. Considering that this calculation was carried out in the limit of asymptotically large t, the extent of its agreement with our measurements, in which the kaon mass still plays a significant kinematic role, is remarkable.

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