LEPTON AND HADRON PAIR PRODUCTION IN TWO-PHOTON REACTIONS

PLUTO Collaboration

Ch. BERGER, H. GENZEL, R. GRIGULL, W. LACKAS and F. RAUPACH
I. Physikalisches Institut der RWTH Aachen [1], *Germany*

A. KLOVNING, E. LILLESTÖL, E. LILLETHUN and J.A. SKARD
University of Bergen [2], *Norway*

H. ACKERMANN, G. ALEXANDER [3], F. BARREIRO, J. BÜRGER, L. CRIEGEE, H.C. DEHNE, R. DEVENISH [4], A. ESKREYS [5], G. FLÜGGE [6], G. FRANKE, W. GABRIEL, Ch. GERKE, G. KNIES, E. LEHMANN, H.D. MERTIENS, U. MICHELSEN, K.H. PAPE, H.D. REICH, M. SCARR [13], B. STELLA [7], T.N. RANGA SWAMY [8], U. TIMM, W. WAGNER, P. WALOSCHEK, G.G. WINTER and W. ZIMMERMANN
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

O. ACHTERBERG, V. BLOBEL [9], L. BOESTEN, V. HEPP [14], H. KAPITZA, B. KOPPITZ, B. LEWENDEL, W. LÜHRSEN, R. van STAA and H. SPITZER
II. Institut für Experimentalphysik der Universität Hamburg [1], *Germany*

C.Y. CHANG, R.G. GLASSER, R.G. KELLOGG, K.H. LAU, R.O. POLVADO, B. SECHI-ZORN, A. SKUJA, G. WELCH and G.T. ZORN
University of Maryland [10], *College Park, MD, USA*

A. BÄCKER [11], S. BRANDT, K. DERIKUM, A. DIEKMANN, C. GRUPEN, H.J. MEYER, B. NEUMANN, M. ROST and G. ZECH
Gesamthochschule Siegen [1], *Germany*

T. AZEMOON [12], H.J. DAUM, H. MEYER, O. MEYER, M. RÖSSLER, D. SCHMIDT and K. WACKER [11]
Gesamthochschule Wuppertal [1], *Germany*

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We have measured the production of charged particle pairs in e^+e^- initiated two-photon reactions. The observed rates and invariant mass spectra agree with expectations from QED if a resonant $\pi^+\pi^-$ production at the f^0 mass is added. Assuming dominance of the helicity 2 production we obtain the width $\Gamma(f^0 \to \gamma\gamma) = 2.3 \pm 0.5$ keV.

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

[3] On leave from Tel Aviv University, Israel.

[4] Now at Oxford University, England.

[5] On leave from Institute of Nuclear Physics, Krakow, Poland.

[6] Now at Universität and Kernforschungszentrum Karlsruhe.

[7] On leave from University of Rome, Italy, partially supported by INFN.

[8] Now at Tata Institute, Bombay, India.

[9] Now at CERN, Geneva, Switzerland.

[10] Partially supported by Department of Energy, USA.

[11] Now at Harvard University, Cambridge, MA, USA.

[12] Now at University College, London, England.

[13] On leave from University of Glasgow, Scotland.

[14] On leave from Heidelberg University.

Two-photon production of lepton and hadron pairs $\gamma\gamma \to ee, \mu\mu, \pi\pi$ can be studied at high energy electron–positron storage rings via the reaction $e^+e^- \to e^+e^-X$, where X is a pair of charged particles (see fig. 1a). These processes are of considerable interest, because lepton-pair production and the point-like production of pion pairs can be calculated in QED. By comparing the measured rate of e.g. lepton pairs with that predicted, one is thus testing QED in processes, the amplitude of which is proportional to the fourth power of the coupling constant e, compared to e^2 in annihilation processes [1]. On the other hand the production of $C = +1$ resonances, which decay into pion pairs, should show up as a deviation from the calculated QED two-prong cross section.

We have investigated two-photon production of charged particle pairs using the detector PLUTO at PETRA, the e^+e^- colliding beam machine at DESY. A description of the experimental set-up can be found in ref. [2]. The data reported in this paper have been taken at beam energies between 15 and 16 GeV ($\langle E_B \rangle = 15.5$ GeV) for an integrated luminosity of 2600 nb^{-1}.

The outgoing electrons and positrons (outer lepton lines in fig. 1a) are very strongly peaked in the forward (backward) direction and are thus not identified for the bulk of our data ("no-tag condition"). We report, however, also on a small subsample of the data, where either the electron or the positron is measured in one of the forward spectrometers ("single-tag condition").

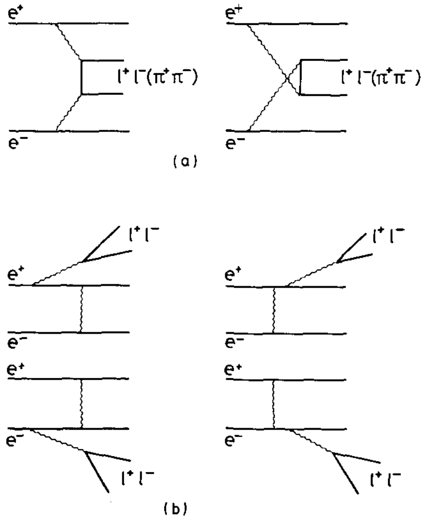

Fig. 1. Feynman diagram for pair production (a) via the two-photon exchange process and (b) the bremsstrahlungprocess ($\ell^+\ell^- = e^+e^-, \mu^+\mu^-$).

The produced pairs (inner lines in fig. 1a) are identified using the central track detector of PLUTO. For the no-tag sample we require two oppositely charged tracks subject to the following conditions:

(a) $|\cos\theta| < 0.56$ for each track,

(b) $p_\perp > 400$ MeV for each track,

(c) acollinearity angle between the tracks $> 15°$.

The polar angle θ and the transverse momentum $p_\perp$ are measured with respect to the beam axis. Events with neutral energy not related to the tracks are rejected. The rather strong conditions (a) and (b) are used to ensure uniform efficiency of the central detector. Condition (c) is needed for rejecting cosmic rays and Bhabha events. The track-selection criteria for tagged events are less stringent and are identical to the ones described in ref. [2].

The vertex distribution of the no-tag events is shown in fig. 2. There is a very clear peak around the interaction point with only a small contamination (≈5%) from beam–gas scattering. In figs. 3a and 3b we plot for the background subtracted no-tag events, the total energy in the central detector and the vector sum of the transverse momenta, $p_\perp^{\mathrm{sum}} = \boldsymbol{p}_\perp^1 + \boldsymbol{p}_\perp^2$.

The energy distribution peaks below 2 GeV and decreases steeply toward higher energies. There are only 5% of all events above a total energy of 10 GeV.

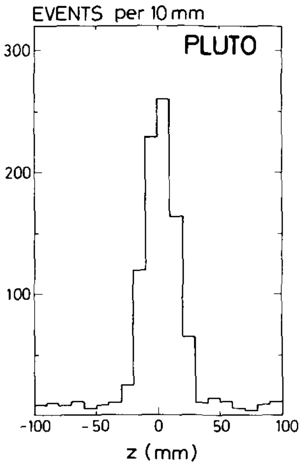

Fig. 2. Distribution of the reconstructed event vertices along the beam line.

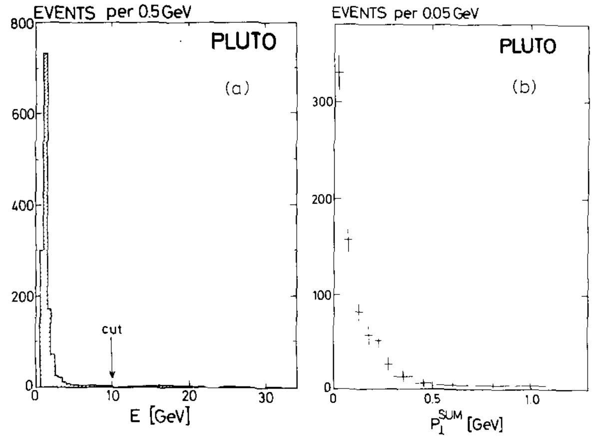

Fig. 3. (a) Background subtracted distribution of the total energy in the central detector and (b) the vector sum of the transverse momenta $p_\perp^{\mathrm{sum}} = |p_\perp^1 + p_\perp^2|$.

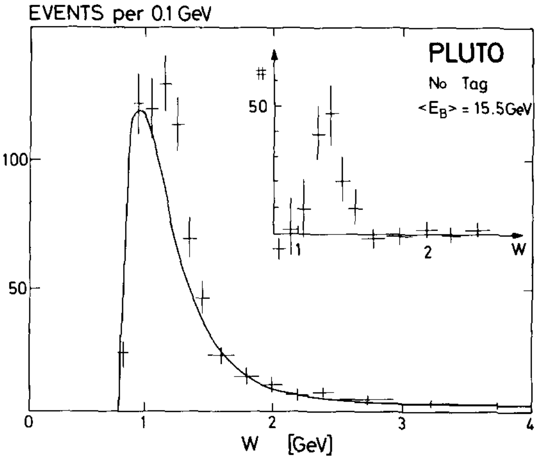

Fig. 4. Invariant mass distribution of the two-prong events. The solid line shows the absolute QED prediction for the production of lepton pairs (ee, $\mu\mu$). The insert shows the difference between the data and the QED prediction.

They are attributed to radiative Bhabha events and are eliminated. The $p_\perp^{\mathrm{sum}}$ distribution demonstrates that the transverse momentum of the two tracks is balanced, i.e. on the average the missing transverse momentum is compatible with zero. Both features strongly support the conclusion that these events originate from two-photon interactions. The energy distribution results from the bremsstrahlungspectrum of the photons and the transverse momentum is balanced because most of the photons are radiated along the direction of the incoming beams. In fact the estimated contribution from annihilation processes which lead to two-prong events with similar characteristics is completely negligible.

In fig. 4 the number of events is plotted versus the invariant mass of the pairs W which is obtained by assigning pion masses to all particles. The solid line is the result of an absolute QED prediction for the production of lepton pairs (ee, $\mu\mu$). It was calculated using a computer program written by Vermaseren [3]. This program includes an exact calculation of the diagrams in fig. 1a plus their interference with bremsstrahlung terms (fig. 1b). Pion-pair production via the two-photon interaction is normally assumed to be small. On the other hand, the acceptance cuts favour pions relative to leptons. We have estimated this contribution by taking the production cross section from ref. [4] and calculating the photon fluxes via the equivalent photon approximation [4,5] [‡1]. The predicted rate is ≈15% of the lepton signal in fig. 4.

A background to the two-prong spectra could result from two photon initiated multi-hadron production with missing particles in the central detector. Using the experimental results and the Monte Carlo method described in ref. [2], we have estimated this background to be smaller than 2% in our data sample.

The agreement of the QED calculation with the data in the bins below 1 GeV and above 1.5 GeV is very good, taking into account the systematic error of our data (≈15%) and the fact that radiative corrections have not been included. There have been very few attempts to calculate radiative corrections to two-photon processes [6]. These corrections are strongly dependent on specific detector cuts. We expect them to reduce the cross section by a few percent [7] and to have a smooth W dependence, in accordance with the good agreement of our data with the shape of the QED curve above 1.5 GeV.

For $1 < W < 1.5$ GeV there is a clear excess of the data above the QED prediction. The insert in fig. 4 (128 ± 27 events) shows the difference between

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[‡1] We used the formula given in ref. [4] which in our range differs by less than 5%.

the data and the QED prediction. It has a typical resonance behaviour. A very good candidate for such a resonance is the $f^0(1270)$. Another possible candidate in the same mass region is the $\epsilon(1300)$. It was rejected mainly because it is believed to have a much larger width ($\Gamma_{tot} > 300$ MeV) [8]. In principle one could distinguish the f^0 from the ϵ hypothesis via the angular distribution of the decay pions. In practice this is not conclusive because of our limited angular acceptance and the large QED background.

For a quantitative comparison we calculate the expected number of events (N^i_{exp}) in each mass bin i from a superposition of lepton-pair production (N^i_{QED}) and f^0 production ($N^i_{f^0}$).

$$N^i_{exp} = aN^i_{QED} + bN^i_{f^0} .$$

In order to determine $N^i_{f^0}$ we simulate production and decay of f^0 mesons ($ee \rightarrow eef^0 \rightarrow ee\pi\pi$) in a Monte Carlo program using

$$d\sigma = \int N(k_1)\,dk_1\,N(k_2)\,dk_2\,\sigma_{\gamma\gamma}(W^2)P(\theta^{cm})\,d\Omega^{cm} ,$$

with a Breit–Wigner ansatz for the total cross section $\sigma_{\gamma\gamma}$ in the reaction $\gamma\gamma \rightarrow f^0 \rightarrow \pi^+\pi^-$:

$$\sigma_{\gamma\gamma}(W^2) = 40\pi \frac{\Gamma_{\gamma\gamma}\Gamma_{\pi^+\pi^-}}{(W^2 - M^2_{f^0})^2 + \Gamma^2 M^2_{f^0}} .$$

$\Gamma_{\pi^+\pi^-}$, Γ and M_{f^0} were taken from the standard-data compilation [8]. The decay width $\Gamma_{\gamma\gamma}$ is arbitrarily set to 1 keV, thus b will be the experimental width in units of keV. $N(k)\,dk$ is the number of photons with energies between k and $k + dk$ radiated from the electron (positron) [5]. Being a $J = 2$ state, the f^0 can be produced via two helicity amplitudes $|\lambda| = 2$, $\lambda = 0$ in photon–photon reactions. These amplitudes lead to different decay angular distributions $P(\theta^{cm})$ in the pion pair center of mass sytem:

$$P(\theta^{cm}) = \frac{15}{32\pi} \sin^4\theta^{cm} , \qquad |\lambda| = 2 .$$

$$P(\theta^{cm}) = \frac{5}{16\pi}(3 \cos^2\theta^{cm} - 1)^2 , \qquad \lambda = 0 .$$

We have chosen $\lambda = 2$, because the dominance of this amplitude is predicted from widely differing theoretical approaches to the problem of radiative f^0 decay [9]. The results of our fit are given by $a = 0.97 \pm 0.05$ and $b = 2.3 \pm 0.5$ ($\chi^2 = 6.5$ for 11 DF). The value of a confirms QED within the errors and limitations discussed above. The fit value for the $\gamma\gamma$ decay width of the f^0 meson is $\Gamma_{\gamma\gamma} = 2.3 \pm 0.5$ keV with an additional systematic error of ±15%. The virtual photon mass squared is very low, $Q^2 = 0.007$ GeV^2 on the average.

The experimental result is to be compared with the numerous theoretical predictions, which are listed in table 1. Our result is close to the value obtained in calculations [10,11] using the non-relativistic quark model with an oscillator potential. With the exception of ref. [12] all methods based on finite energy sum rules, tensor meson dominance etc. lead to larger values for $\Gamma_{\gamma\gamma}$. It should be noted also that tentatively assuming the $\lambda = 0$ hypothesis we find $\Gamma_{\gamma\gamma} = 5.7 \pm 1.3$ keV.

Finally we have analyzed the much smaller data sample with the single-tag condition, i.e. an electron (positron) scattered into one of the small-angle taggers, SAT, of the forward spectrometers [2]. The invariant mass distribution is shown in fig. 5 along with the QED prediction. The small enhancement in the f^0 mass region can be attributed to f^0 production via one almost real (as above) and one virtual ($Q^2 = 0.28$ GeV^2) photon. Due to the limited statistics we only give an upper limit of $\Gamma_{\gamma^*\gamma} < 2.6$ keV (95% confidence level) again using the $\lambda = 2$ hypothesis. For extracting this radiative width the flux factor for the virtual photons radiated from the electron scattered into the SAT was taken from the $e\gamma$ scattering formalism described in ref. [2].

Table 1
Theoretical predictions for $\Gamma(f^0 \rightarrow \gamma\gamma)$.

Ref.	$\Gamma_{\gamma\gamma}$ (keV)
12	0.8
13	> 1
10	1.2–2.3
11	2.6
14	5.07
15	7
16	5.7
17	8
9	8
18	9.2
19	11.3
20	21 ± 6
21	28
this exp.	2.3 ± 0.5

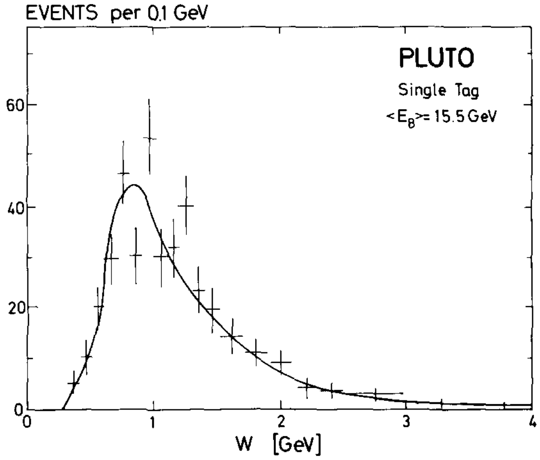

Fig. 5. Invariant mass distribution of the two-prong events with a single tag in the SAT.

In summary we have measured particle-pair production in two-photon processes over a wide range of invariant masses. Outside the f^0-resonance region the invariant mass distribution agrees with QED predictions. The radiative width of the f^0 meson has been determined for the first time and an upper limit has been given for its production via virtual photons.

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