DIFFERENTIAL CROSS SECTIONS FOR $\gamma\gamma \to p\bar{p}$ IN THE CM ENERGY RANGE FROM 2.0 TO 3.1 GeV

TASSO Collaboration

M. ALTHOFF, W. BRAUNSCHWEIG, K. GATHER, F.J. KIRSCHFINK, K. LÜBELSMEYER, H.-U. MARTYN, G. PEISE, J. RIMKUS, P. ROSSKAMP, H.G. SANDER, D. SCHMITZ, H. SIEBKE, W. WALLRAFF
I. Physikalisches Institut der RWTH Aachen, Germany [1]

H.M. FISCHER, H. HARTMANN, W. HILLEN [2], A. JOCKSCH, G. KNOP, L. KÖPKE, H. KOLANOSKI, H. KÜCK, R. WEDEMEYER, N. WERMES [3], M. WOLLSTADT
Physikalisches Institut der Universität Bonn, Germany [1]

S. COOPER, Y. EISENBERG [4], H. HULTSCHIG, P. JOOS, W. KOCH, U. KÖTZ, H. KOWALSKI, A. LADAGE, B. LÖHR, D. LÜKE, P. MÄTTIG, K.H. MESS, D. NOTZ, J. PYRLIK, D.R. QUARRIE [5], M. RUSHTON, W. SCHÜTTE, D. TRINES, G. WOLF, Ch. XIAO
Deutsches Elektronen-Synchrotron, DESY, Hamburg, Germany

R. FOHRMANN, E. HILGER, T. KRACHT, H.L. KRASEMANN, P. LEU, E. LOHRMANN, D. PANDOULAS, G. POELZ, B.H. WIIK
II. Institut für Experimentalphysik der Universität Hamburg, Germany [1]

I. AL-AGIL, R. BEUSELINCK, D.M. BINNIE, A.J. CAMPBELL, P.J. DORNAN, B. FOSTER, D.A. GARBUTT, T.D. JONES, W.G. JONES, J. McCARDLE, J.K. SEDGBEER
Department of Physics, Imperial College London, England [6]

K.W. BELL, M.G. BOWLER, I.C. BROCK [7], R.J. CASHMORE, P.E.L. CLARKE, R. DEVENISH, P. GROSSMANN, S.L. LLOYD, G.L. SALMON, J. THOMAS, T.R. WYATT, C. YOUNGMAN
Department of Nuclear Physics, Oxford University, England [6]

J.C. HART, J. HARVEY, J. PROUDFOOT, D.H. SAXON, P.L. WOODWORTH
Rutherford Appleton Laboratory, Chilton, England [6]

F. BARREIRO, M. DITTMAR, D. HEYLAND, M. HOLDER, B. NEUMANN
Fachbereich Physik der Universität-Gesamthochschule Siegen, Germany [1]

E. DUCHOVNI, U. KARSHON, G. MIKENBERG, R. MIR, D. REVEL, E. RONAT, A. SHAPIRA, G. YEKUTIELI
Weizmann Institute, Rehovot, Israel [8]

and

T. BARKLOW, A. CALDWELL, M. CHERNEY, J.M. IZEN, M. MERMIKIDES, G. RUDOLPH, D. STROM, H. VENKATARAMANIA, E. WICKLUND, SAU LAN WU and G. ZOBERNIG
Department of Physics, University of Wisconsin, Madison, WI, USA [9]

Received 12 August 1983

For footnotes see next page.

0.031-9163/83/0000–0000/$ 03.00 © 1983 North-Holland

Exclusive production of proton–antiproton pairs by two photon scattering at CM energies between 2.0 GeV and 3.1 GeV has been measured with the TASSO detector at the e^+e^- storage ring PETRA. The angular distribution is flat within the accepted CM angular range $|\cos\Theta^*| \leqslant 0.7$. The integrated cross section ($|\cos\Theta^*| \leqslant 0.6$) drops from about 4 nb at 2 GeV to less than 0.5 nb above 3 GeV. For the two-photon production of the $\eta_c(2984)$ and its subsequent decay into proton–antiproton the upper limit $\Gamma(\eta_c \to \gamma\gamma)\cdot B(\eta_c \to p\bar{p}) < 0.32$ keV (95% CL) is found.

First results on proton–antiproton pair production by two photon collisions via the reaction $e^+e^- \to e^+e^- p\bar{p}$ were presented by us in ref. [1]. In this paper we present a measurement of the angular dependence and the energy behaviour of the cross section for $\gamma\gamma \to p\bar{p}$ obtained with an increase in statistics by a factor of 10. The results are compared with predictions of QCD [2].

The experiment was performed with the TASSO detector at the DESY storage ring PETRA. A description of the detector can be found elsewhere [3]. The data sample corresponds to an integrated luminosity of 74 pb^{-1} at beam energies mainly around 17 GeV taken with one of the following triggers [4]: (1) any two coplanar charged particles having associated signals in the inner time-of-flight counters separated by more than 154° in azimuth, or (2) two or more charged particles originating from the interaction region within ±15 cm along the beamline. The charged particle tracks are found in the central chambers by a hardware processor, whose track finding efficiency depends on the component $|p_\perp|$ of the momentum transverse to the beam direction. For the majority of the data the track finding efficiency was about 50% for tracks with transverse momenta of 0.17 GeV/c rising to 95% above 0.29 GeV/c. The trigger did not require the detection of the scattered electrons.

Candidates for two-photon produced two-prong events were selected requiring two oppositely charged particles in the central detector. The polar angles Θ of the tracks with respect to the beam axis were restricted to $|\cos\Theta| \leqslant 0.8$. In order to minimize uncertainties originating from energy loss, nuclear absorption and multiple scattering the observed momentum of each track had to be larger than 0.35 GeV/c. Photon–photon events with unobserved particles were rejected by demanding the vector sum of the transverse momenta of the two particles ($|\Sigma \boldsymbol{p}_\perp|$) to be less than 0.1 GeV/c. For particle identification we used time-of-flight measurements from the 48 scintillation counters surrounding the cylindrical drift chamber. Since the time-of-flight (TOF) separation of protons from the lighter particles deteriorates with increasing particle momentum, the momentum of each track had to be lower than 1.6 GeV/c corresponding roughly to a 2σ (3σ) TOF separation of kaons (pions) from protons. These cuts also remove background contributions from one-photon annihilation processes.

For each particle selected by these cuts the square of the mass (m^2_{TOF}) was calculated from its track length, momentum and time-of-flight. In fig. 1a m^2_{TOF} of the positive particle is plotted versus m^2_{TOF} of the negative particle. Most of the events are electron, muon or pion pairs and cluster around zero. In this analysis we do not distinguish these three particle types and will refer to them as "pions". In addition there is a sample of kaon pairs [4], a cluster in the "π^-"p-region and a well separated cluster of proton–antiproton events. The events in the "π^-p"-band are found to be produced mainly by beam–gas interactions.

To select proton–antiproton pairs three gaussian weights (n = "π", K, p)

$$W(n) = \exp(-(t_{\mathrm{meas}} - t_n)^2/2\sigma^2),$$

are assigned to each particle, corresponding to the three hypotheses for the particle to be a "pion", kaon or proton. Here t_{meas} is the measured TOF and t_n is the calculated TOF for hypothesis n. The resolution σ of the difference ($t_{\mathrm{meas}} - t_n$) is given by

[1] Supported by the Deutsches Bundesministerium für Forschung und Technologie.
[2] Now at Philips, Aachen, Germany.
[3] Now at SLAC, Stanford, CA, USA.
[4] On leave from Weizmann Institute, Rehovot, Israel.
[5] Now at FNAL, Batavia, IL, USA.
[6] Supported by the UK Science and Engineering Research Council.
[7] Now at Carnegie-Mellon University, Pittsburg, USA.
[8] Supported by the Minerva Gesellschaft für Forschung mbH.
[9] Supported by the US Department of Energy contract WY-76-C-02-0881.

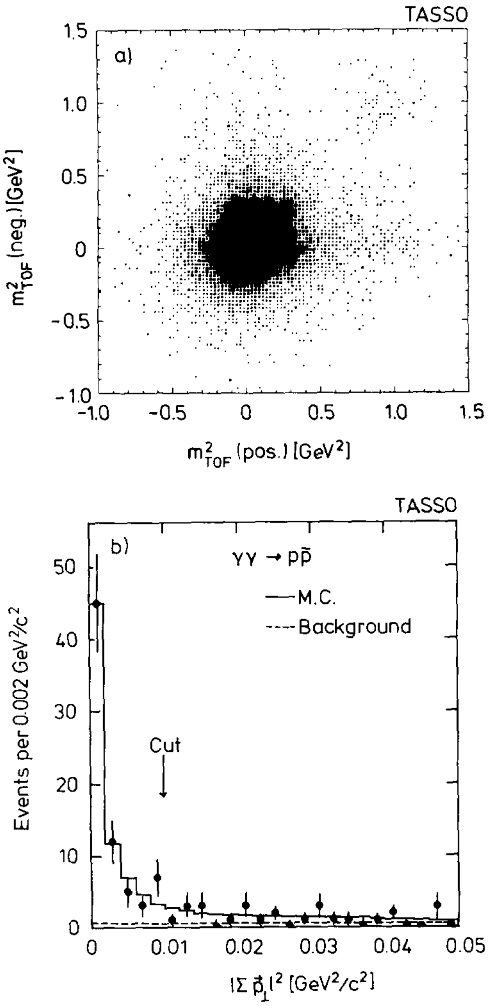


Fig. 1. (a) m^2_{TOF} of the positive track versus m^2_{TOF} of the negative track. All but the TOF cuts have been applied to the data. (b) Distribution of $|\Sigma \boldsymbol{p}_\perp|^2$ for candidate events for the reaction $\gamma\gamma \to p\bar{p}$.

$$\sigma^2 = \sigma^2_{meas} + \sigma^2_n .$$

σ_{meas} is the rms time resolution (265–455 ps) depending on the position of the hit along the TOF counter and σ_n is the uncertainty of the calculated time resulting from the resolutions of the track length and the momentum in the central detector. Both contributions are comparable for proton momenta around 0.45 GeV/c. The weight W(p) for each track had to be consistent with the proton hypothesis within three standard deviations.

To separate proton–antiproton pairs from "π" "π", "π"K, KK, "π"p pairs the following cuts were applied to the event weights, i.e. to the products of the particle weights:

$$W(p)\cdot W(\bar{p}) \geqslant 1000\cdot 10\cdot W(\pi^+)\cdot W(\pi^-),$$

$$W(p)\cdot W(\bar{p}) \geqslant 6\cdot 10\cdot W(\pi\pm)\cdot W(K\mp),$$

$$W(p)\cdot W(\bar{p}) \geqslant 1\cdot 10\cdot W(\pi^+)\cdot W(\bar{p}),$$

$$W(p)\cdot W(\bar{p}) \geqslant 5\cdot 10\cdot W(\pi^-)\cdot W(p),$$

$$W(p)\cdot W(\bar{p}) \geqslant 10\cdot 10\cdot W(K^+)\cdot W(K^-).$$

The factors 1000, 6, 1, 5 and 10 take roughly account of the observed relative abundances of the different particle pairs. The additional factor 10 suppresses background from misidentified particles.

Applying all the cuts described above to the data sample we obtain 72 proton–antiproton events produced by photon–photon interactions. To demonstrate that these events are exclusively produced proton–antiproton pairs we plot in fig. 1b the distribution of the squared vector sum of the transverse momenta of both tracks ($|\Sigma \boldsymbol{p}_\perp|^2$) without the transverse momentum balance cut. The distribution peaks at zero as expected for $\gamma\gamma$-events with no missing particles. The $|\Sigma \boldsymbol{p}_\perp|^2$-distribution of the data has been compared to the corresponding distribution obtained from a Monte Carlo simulation of $\gamma\gamma \to p\bar{p}$ events (see below). A background contribution from events with non-detected particles is expected to have a flat distribution in $|\Sigma \boldsymbol{p}_\perp|^2$. This background contribution was determined by fitting the sum of the Monte Carlo distribution for $\gamma\gamma \to p\bar{p}$ and a constant term to the experimental distribution in the range $0 < |\Sigma \boldsymbol{p}_\perp|^2 < 0.05$ GeV$^2/c^2$. From this fit we found that below $|\Sigma \boldsymbol{p}_\perp| < 0.1$ GeV/c the background from events with missing particles is 2 events.

The background of misidentified proton–antiproton pairs was estimated from the scatter-plot in fig. 1a to be less than 2 events. The background from beam–gas reactions is found to be less than 1 event. In total the estimated background is 5 of the 72 proton–antiproton events.

The detection efficiency ϵ was determined with a Monte Carlo program simulating the reaction $e^+e^- \to e^+e^-\ p\bar{p}$ in the detector. Events were generated according to

$$\frac{d\sigma_{e^+e^-\to e^+e^- p\bar{p}}}{dW_{\gamma\gamma}\, d\omega\, d\cos\Theta^*} = \frac{dL(W_{\gamma\gamma},\omega)}{dW_{\gamma\gamma}\, d\omega} \times \frac{d\sigma_{\gamma\gamma\to p\bar{p}}(W_{\gamma\gamma},\cos\Theta^*)}{d\cos\Theta^*},$$

where ω represents all kinematical variables of the two-photon system other than the invariant mass ($W_{\gamma\gamma}$). $L(W_{\gamma\gamma},\omega)$ is the two-photon luminosity function [5] and Θ^* is the production angle measured in the $\gamma\gamma$-CM system. The cross section for $\gamma\gamma \to p\bar{p}$ was assumed to be independent of $W_{\gamma\gamma}$ and $\cos\Theta^*$. The simulation of the detector included energy loss, multiple scattering and nuclear interactions. The generated events were passed through the same cuts as described above. The detection efficiency was found to be $1.0 \pm 0.17\%$ at $W_{\gamma\gamma} = 2.0$ GeV, $6.5 \pm 0.6\%$ at 2.5 GeV and $3.0 \pm 0.6\%$ at 3.1 GeV (see fig. 2a). The rise above the kinematical threshold is caused by the lower momentum cut while the decrease above 2.5 GeV is due to the TOF cuys. The error of the detection efficiency is dominated at small $W_{\gamma\gamma}$ by the uncertainties of the energy loss and nuclear interactions and above 2.8 GeV by the TOF resolution.

The uncorrected invariant mass distribution of the proton–antiproton events is given in fig. 2a. In fig. 2b we give the cross section integrated over the angular range $|\cos\Theta^*| \leqslant 0.6$. The integrated cross section is large above threshold and decreases rapidly with increasing $W_{\gamma\gamma}$; it is about 4 nb at 2 GeV and smaller than 0.5 nb above 3 GeV. In our previous analysis we obtained a total cross section of 4.6 ± 1.6 nb for 2.0 GeV $< W_{\gamma\gamma} <$ 2.6 GeV assuming a flat angular distribution [1]. This value corresponds to an integrated cross section of 2.8 ± 0.5 nb for $|\cos\Theta^*| \leqslant 0.6$ which is in good agreement with the new data points.

We studied the angular distribution of the process $\gamma\gamma \to p\bar{p}$ for two mass bins (2.0 GeV $\leqslant W_{\gamma\gamma} \leqslant$ 2.4 GeV and 2.4 GeV $< W_{\gamma\gamma} \leqslant$ 2.8 GeV). The uncorrected $\cos\Theta^*$-distributions of the proton–antiproton events are given in figs. 3a, 3b together with the de-

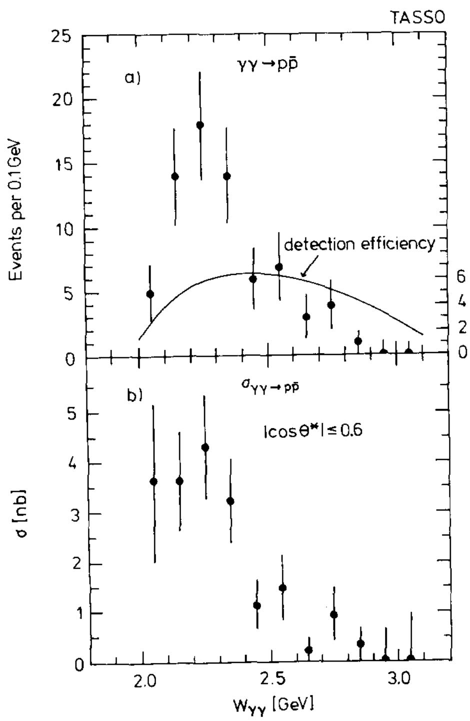
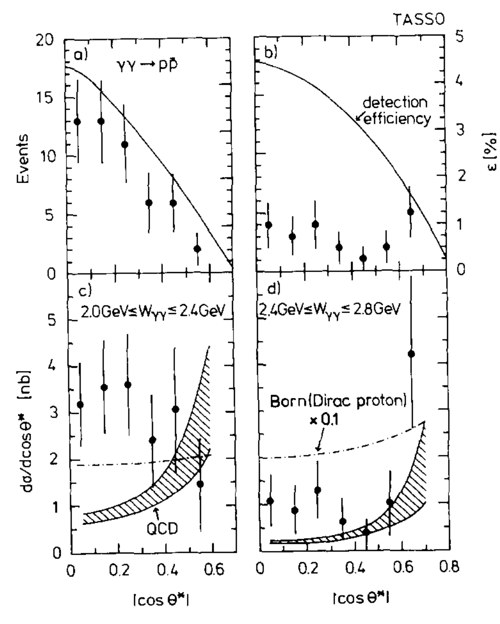


Fig. 2. (a) Uncorrected invariant mass distribution of $p\bar{p}$ events and energy dependence of the detection efficiency ϵ (full line). (b) Cross section for $\gamma\gamma \to p\bar{p}$ integrated over the angular range $|\cos\Theta^*| \leqslant 0.6$.



Figs. 3(a), (b). Uncorrected distribution of the proton scattering angle in the $\gamma\gamma$ CM system and the angular dependence of the detection efficiency ϵ (full line). (c),(d) Differential cross section $d\sigma/d\cos\Theta^*$ of $\gamma\gamma \to p\bar{p}$ for 2.0 GeV $\leqslant W_{\gamma\gamma} \leqslant$ 2.4 GeV and 2.4 GeV $< W_{\gamma\gamma} \leqslant$ 2.8 GeV. The data are compared to predictions of the Born approximation for Dirac protons and to a QCD calculation.

tection efficiency. The detection efficiency is largest for $\cos\Theta^* = 0$ and decreases smoothly toward forward angles reaching zero at $|\cos\Theta^*| \geqslant 0.8$ because of the cut in the laboratory polar angle. The corrected differential cross section $d\sigma/d\cos\Theta^*$ is shown in figs. 3c, 3d for both mass regions. The error bars indicate the statistical errors of the data points. Within the errors the measured cross section is in agreement with a flat angular distribution over the accepted angular range. The hypothesis of a constant differential cross section gives a χ^2 of 3.3 (6.1) in the case of the lower (higher) mass bin for 5 (6) degrees of freedom.

The η_c meson at 2.984 ± 0.004 GeV [6] has positive C-parity and can therefore couple to two photons. We looked for its formation in the reaction $\gamma\gamma \to \eta_c \to p\bar{p}$. The mass resolution of the detector is 0.038 GeV in this mass range. No event was observed in the mass range 2.984 ± 0.076 GeV yielding the upper limit on the product of the $\gamma\gamma$-width times the branching ratio of the η_c to $p\bar{p}$:

$$\Gamma(\eta_c \to \gamma\gamma)\cdot B(\eta_c \to p\bar{p}) < 0.32 \text{ keV } (95\% \text{ CL}).$$

We compared our cross section data for $\gamma\gamma \to p\bar{p}$ with a Born term calculation assuming the protons to be pointlike Dirac particles with a pure QED coupling to the photons. The size of the predicted cross section is roughly one order of magnitude larger than observed (see figs. 3c, 3d). The discrepancy is even larger (e.g. at $W_{\gamma\gamma} = 2.0$ GeV by roughly a factor of 200), if the anomalous magnetic moment of the proton is included in the calculation [7].

Recently the differential cross section of $\gamma\gamma \to p\bar{p}$ has been calculated within the framework of perturbative QCD [2]. The basic feature of this calculation is the factorization of the scattering amplitude into a quark scattering part and a distribution function for the valence quarks in the proton. The domain of validity of this calculation is the region of large four momentum transfers, i.e. large $W_{\gamma\gamma}$ and large scattering angles. The four momentum transfer squared between photon and proton for $\cos\Theta^* = 0$ varies from 2.0 to 3.0 GeV^2 (1.1–2.0 GeV^2) for the higher (lower) mass bin. We extrapolate the results of [2] from the J/ψ mass region into the $W_{\gamma\gamma}$ range of our data. The extrapolation is given as shaded bands in figs. 3c, 3d. The widths of the bands represent the spread of cross sections obtained for different choices of the distribution function. The cross section values predicted around $\cos\Theta^* = 0$ are a factor of ~3–5 smaller than the measured ones.

To summarize, we have measured differential cross sections of the reaction $\gamma\gamma \to p\bar{p}$ for 2.0 GeV $\leqslant W_{\gamma\gamma} \leqslant$ 3.1 GeV and $|\cos\Theta^*| \leqslant 0.7$. Within this kinemaical region the angular distributions are flat. The integrated cross section ($|\cos\Theta^*| \leqslant 0.6$) is large above threshold and decreases rapidly towards higher $W_{\gamma\gamma}$. The observed cross section is an order of magnitude smaller than predicted by the Born approximation for pointlike Dirac protons. Around $\cos\Theta^* = 0$ the cross section values calculated within the framework of QCD are considerably lower than the measured data. An upper limit has been derived for the product $\Gamma(\eta_c \to \gamma\gamma)\cdot B(\eta_c \to p\bar{p}) < 0.32$ keV (95% CL).

We gratefully acknowledge the support by the DESY directorate and the PETRA machine group. We wish to thank the technical service groups at DESY and all the engineers and technicians at the collaborating institutions for their invaluable help. A large fraction of the data reduction has been done with our 168-emulators. We want to express our sincere gratitude to P. Kunz, SLAC, for his advice and assistance in this matter and for building one of the emulators. We are grateful to H. Brafman, A. Jacob and R. Yaari of the Weizmann Institute for their invaluable help in the construction, installation and testing of the 168-emulators. We are grateful to Drs. P.H. Damgaard and W. Pfeil for useful discussions. One of us (Y.E.) wishes to thank the Minna-James-Heineman Stiftung of Hannover for partial support. Those of us from outside DESY wish to thank the DESY directorate for the hospitality extended to us while working at DESY.

References

[1] TASSO Collab., R. Brandelik et al., Phys. Lett. 108B (1982) 67.
[2] P.H. Damgaard, Nucl. Phys. B211 (1983) 435.
[3] TASSO Collab., R. Brandelik et al., Z. Phys. C4 (1980) 87; Phys. Lett. 83B (1979) 621.
[4] TASSO Collab., M. Althoff et al., Phys. Lett. 121B (1983) 216.
[5] J.H. Field, Nucl. Phys. B168 (1980) 477 (and Erratum).
[6] J. Gaiser et al., SLAC-PUB-2899, to be published in Phys. Rev. Lett.
[7] N. Arteaga-Romero, College de France preprint, LPC 82-06 (Paris, 1983).