A MEASUREMENT OF $\gamma\gamma \to \rho^+\rho^-$

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The reaction $\gamma\gamma\to\rho^+\rho^-\to\pi^+\pi^-\pi^0\pi^0$ has been studied with the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. Near threshold, the cross section for this reaction is about four times smaller than for the reaction $\gamma\gamma\to\rho^0\rho^0$.

We report on the first cross section measurement of the reaction $\gamma\gamma\to\rho^+\rho^-$. Previously only upper limits existed for this reaction [1]. They indicated a much lower cross section than that for the reaction $\gamma\gamma\to\rho^0\rho^0$ which exhibits a large threshold enhancement [2]. This excludes the possibility that the two-photon production of ρ pairs near threshold is dominated by the formation of an isospin zero resonance which would decay two times more frequently to $\rho^+\rho^-$ than to $\rho^0\rho^0$. On the other hand, $q\bar{q}q\bar{q}$ models predicted the suppression of the $\rho^+\rho^-$ channel due to interference between degenerate states with isospin zero and two, respectively [3,4]. Non-resonant contributions to two-photon production of ρ pairs have been estimated using a *t*-channel factorisation approach [5,6]. The non-resonant $\rho^+\rho^-$ cross section has also been estimated by evaluating leading QCD diagrams [7].

The measurement of the reaction $\gamma\gamma\to\rho^+\rho^-$ reported here is based on a data sample, corresponding to an integrated luminosity of 234 pb^{-1}, collected with the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The beam energy varied between 4.7 and 5.3 GeV. ARGUS is a universal magnetic detector with cylindrical symmetry and is described elsewhere [8]. This analysis depends on the capabilities of the detector for good momentum resolution and identification of charged particles, and in particular, on the high sensitivity and good energy resolution for photons.

Candidate events for the reaction $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$ were selected by requiring two oppositely charged particles from a common event vertex. No other charged particles were allowed in the detector. The two charged particles had to be identified as pions with likelihood ratios larger than 5%. Exactly four photons were required with minimum energies of 50 MeV. These had to form at least two π^0 candidates, defined as combinations of two photons with invariant masses between 60 and 220 MeV/c^2. The opening angle between the two photons was required to be smaller than 90° in order to reduce the combinatorial background. The π^0 candidates were constrained to the π^0 mass by a kinematical fit. In events with more than two π^0 candidates, only the two which resulted in the smallest total transverse momentum, p_T, for the event were used. This cut was motivated by the fact that two-photon reactions result in final states with predominantly small total p_T. It is therefore very effective in removing accidental π^0 candidates. The efficiency for assigning the correct photons to a π^0 is larger than 95%.

The selection of two-photon events was made using the same techniques as described in our earlier reports on vector meson pair production in two-photon reactions (see e.g. ref. [9]). The scalar momentum sum of the four pions was required to be less than 3.5 GeV/c. The distribution of the square of the total transverse momentum, p_T^2, was fitted with a function derived from the p_T^2 distribution of Monte Carlo simulated $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$ reactions. A term, assumed to be linear, was added to allow for background from

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incompletely reconstructed events and τ-pair events. By requiring p_T to be less than 100 MeV/c, 1332 events were selected. Out of those, 67 background events were estimated from the fit. Another type of background arises from the signal reaction itself, $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$, where one or more photons from the π^0 decays are lost simultaneously as the same number of fake photons appear due to noise in the electromagnetic calorimeter. This background has a p_T^2 distribution similar to that of the correctly reconstructed events, and was estimated by Monte Carlo simulation to contribute 62 events. Therefore, the finally selected data sample contained 1203 events from the reaction $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$.

A Monte Carlo program was used to simulate collisions between two transverse photons [10]. The events were generated with a constant two-photon cross section, and isotropic phase-space was used for the final state $\pi^+\pi^-\pi^0\pi^0$. In the case of other final states like $\rho^+\rho^-$, the Monte Carlo generated $\pi^+\pi^-\pi^0\pi^0$ events were reweighted with the relevant matrix elements (see below). The events were generated with a beam energy distribution corresponding to that of the data, and a detailed detector and trigger simulation was performed. The simulation of noise in the electromagnetic calorimeter was derived from data using two methods. The first used the $\pi^+\pi^-$ transition between $\Upsilon(2S)$ and $\Upsilon(1S)$, where $\Upsilon(1S)$ decayed to an e^+e^- or $\mu^+\mu^-$ pair. The second method used cosmic rays in coincidence with the beam crossing. In both cases, about 18% of the events were found to contain at least one fake photon due to noise in the electromagnetic calorimeter.

The topological cross section versus $W_{\gamma\gamma}$ for the reaction $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$ is shown in fig. 1. Above 1.2 GeV/c^2 it rises steeply to about 70 nb with a shoulder around 2 GeV/c^2. There are also some events with $W_{\gamma\gamma}$ below 1 GeV/c^2. For example, one would expect the production of $a_0(980)\to\eta\pi$, which, however, is not further investigated here. The systematic uncertainty in the overall scale of all cross sections given in this article is estimated to be 13.5% by adding the following contributions in quadrature: luminosity measurement 3%; trigger simulation 5%; event generation and detector simulation 11%; and background estimations 5%. The systematic uncertainties are not included in the figures.

The production of charged ρ mesons is demonstrated in fig. 2. Fig. 2a shows a scatter plot with the

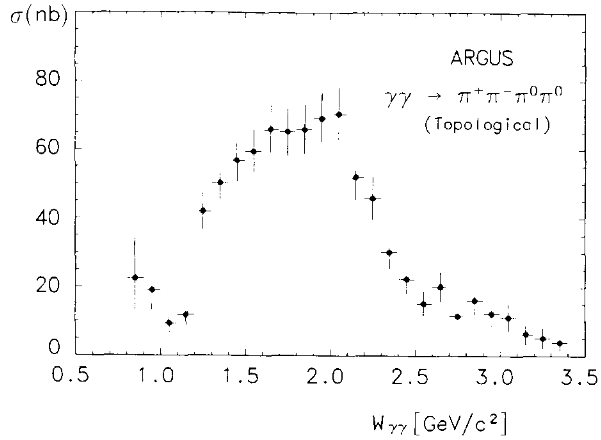

Fig. 1. Topological cross section for $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$ versus $W_{\gamma\gamma}$.

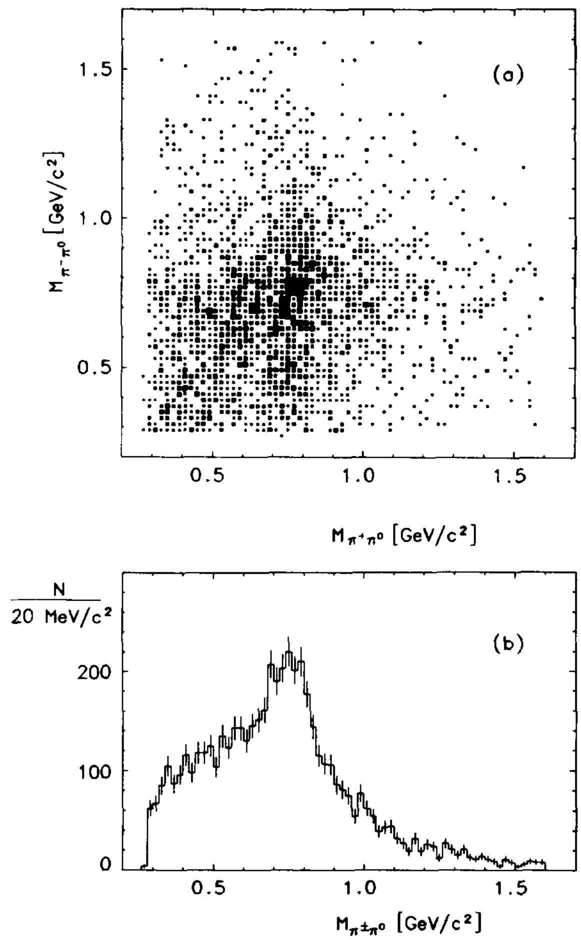

Fig. 2. (a) Scatter plot of the mass of $\pi^-\pi^0$ versus the mass of $\pi^+\pi^0$ combinations (two entries per event). (b) Invariant $\pi^\pm\pi^0$ mass spectrum (four entries per event).

invariant mass of the $\pi^+\pi^0$ and of the $\pi^-\pi^0$ combinations on the two axes, respectively. The clear enhancement in the $\rho^+\rho^-$ region indicates the presence of $\gamma\gamma\to\rho^+\rho^-$ events in the data. The sum of the two projections of the scatter plot shows a prominent $\rho^\pm$ signal (fig. 2b). In view of the limited statistics, we made two reasonable assumptions to determine the cross section for $\gamma\gamma\to\rho^+\rho^-$. The three final states $\rho^+\rho^-$, $\rho^\pm\pi^\mp\pi^0$, and non-resonant $\pi^+\pi^-\pi^0\pi^0$ were assumed to be produced incoherently, and to decay isotropically into four pions. With these two assumptions, the three separate cross sections were derived using a maximum likelihood procedure.

The differential cross section for the reaction $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$, proceeding via the intermediate state i, was parametrized for fixed $W_{\gamma\gamma}$ by

$$d\sigma/d\xi = CW_4(W_{\gamma\gamma})\,|g_i(\xi)|^2 \quad (i=\rho\rho,\ \rho2\pi,\ 4\pi)\ ,$$

where C is a constant, W_4 the $\pi^+\pi^-\pi^0\pi^0$ phase-space, and g_i the matrix element for the state i. The symbol ξ represents the set of seven variables needed, in general, to describe the four-pion system

$$\xi = (m_{12}, m_{34}; \theta_\rho^{12}, \theta_\pi^{12}, \phi_\pi^{12}, \theta_\pi^{34}, \phi_\pi^{34})\ ,$$

where the numbers 1, ..., 4 refer to the four pions using the convention: $\pi_1^+\pi_2^0\pi_3^-\pi_4^0$. The variable m_{ij} denotes the invariant mass of two pions i and j, θ_ρ^{ij} the production angle of the system ij in the $\gamma\gamma$ center-of-mass system, and θ_π^{ij} and ϕ_π^{ij} the polar and azimuthal angles of the pions in the ij center-of-mass system. Our assumptions above remove the angular dependence from the matrix elements g_i, which therefore depend on the invariant two pion masses m_{ij} only. The symmetrized $\rho^+\rho^-$ matrix element is

$$g_{\rho\rho} = (1/\sqrt{2})\,[\mathrm{BW}(m_{12})\mathrm{BW}(m_{34}) + \mathrm{BW}(m_{14})\mathrm{BW}(m_{23})]\ ,$$

where BW denotes the Breit–Wigner amplitude [11]

$$\mathrm{BW}(m) = \frac{\sqrt{m_\rho \Gamma_\rho m/p^*}}{\pi(m_\rho^2 - m^2 - \mathrm{i}m_\rho\Gamma_\rho)}\ ,$$

$$\Gamma_\rho = \Gamma_0 \left(\frac{p^*}{p_0^*}\right)^3 \frac{2p_0^{*2}}{p_0^{*2}+p^{*2}}\ ,$$

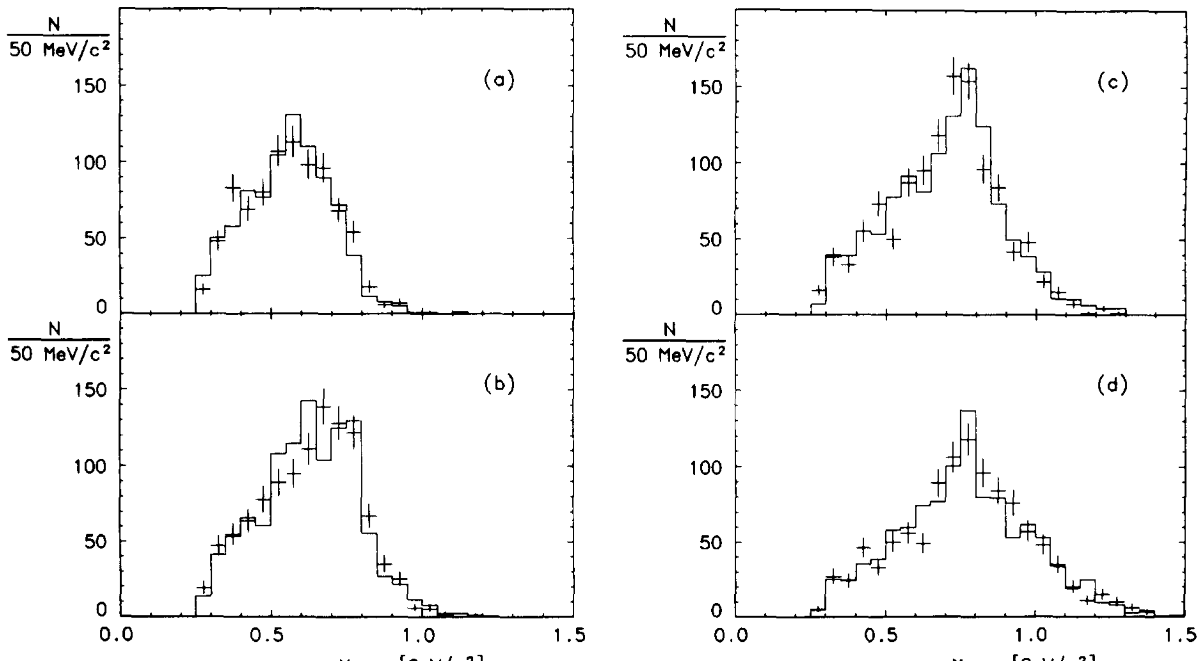

Fig. 3. Comparison of the invariant $\pi^\pm\pi^0$ mass distributions in data (crosses) with the Monte Carlo expectations (histogram) using the fractions as derived from the fit. The comparison is made for four $W_{\gamma\gamma}$ bins. (a) $1.2 \leqslant W_{\gamma\gamma} \leqslant 1.4$ GeV/c^2; (b) $1.4 \leqslant W_{\gamma\gamma} \leqslant 1.6$ GeV/c^2; (c) $1.6 \leqslant W_{\gamma\gamma} \leqslant 1.8$ GeV/c^2; (d) $1.8 \leqslant W_{\gamma\gamma} \leqslant 2.0$ GeV/c^2.

$$p^* = \tfrac{1}{2}\sqrt{m^2 - 4m_\pi^2}, \quad p_0^* = \tfrac{1}{2}\sqrt{m_\rho^2 - 4m_\pi^2} ,$$

$$m_\rho = 770 \text{ MeV}, \quad \Gamma_0 = 150 \text{ MeV} .$$

The $\rho^\pm\pi^\mp\pi^0$ matrix element is

$$g_{\rho 2\pi} = \tfrac{1}{2}[\text{BW}(m_{12}) + \text{BW}(m_{32}) + \text{BW}(m_{14}) + \text{BW}(m_{23})] ,$$

and for non-resonant four-pion production

$$g_{4\pi} = 1 .$$

The fractions, λ_i, of each of the three contributing final states were determined using the maximum likelihood function

$$\Lambda = \prod_n \sum_i \lambda_i P_i(\xi_n) ,$$

with the constraints

$$\sum \lambda_i = 1, \quad \lambda_i \geqslant 0 \quad (i = \rho\rho, \rho 2\pi, 4\pi) .$$

The product runs over all the events, n, and the quantity $P_i(\xi_n)$ is the normalized probability of event n with measured variables ξ_n to be of the kind i,

$$P_i(\xi_n) = \frac{A(\xi_n)\, \mathrm{d}\sigma_i(\xi_n)/\mathrm{d}\xi}{\int A(\xi)\, \mathrm{d}\sigma_i(\xi)} ,$$

where $A(\xi)$ is the detector acceptance calculated using the Monte Carlo program referred to above. We also allowed the fractions λ_i to take on negative values. The results did not change within errors.

Finally the fit maximizes the quantity

$$\sum_n \left[\ln\left(\sum_i \lambda_i \frac{|g_i(\xi_n)|^2}{\int A(\xi)\, \mathrm{d}\sigma(\xi)} \right) - \sum_i \lambda_i \right] .$$

To check the results from the fit, a comparison was made between the $m_{\pi^\pm\pi^0}$ spectra in data and Monte Carlo. For the Monte Carlo distributions, the fitted fractions for the different final states were used, and the respective $m_{\pi^\pm\pi^0}$ spectra were added. The comparison is shown in fig. 3, demonstrating the reliability of the procedure.

The cross sections derived from the fit are shown in fig. 4. The measured cross sections show a smooth behaviour with no significant structures. The $\rho^+\rho^-$ cross section is about a factor four smaller that the $\rho^0\rho^0$ cross section [2], in the range 1.2–2.0 GeV/c^2. The upper limits from JADE for $\gamma\gamma\to\rho^+\rho^-$ [1] are consistent with our measurements. Hence we confirm the main qualitative prediction of the $q\bar{q}q\bar{q}$ models that the two-photon production of $\rho^+\rho^-$ must be suppressed relative to that of $\rho^0\rho^0$. The $q\bar{q}q\bar{q}$ models, in addition, predict a dominance of $J^P = 2^+$ states, so that a spin–parity analysis is necessary for a quantitative test. The present cross section lies between the two model predictions [3,4]. The t-channel factorization has been used [5] to estimate the $\rho^+\rho^-$ cross section only in the range 2 GeV/$c^2 \leqslant W_{\gamma\gamma} \leqslant 3$ GeV/c^2, in reasonable agreement with the data. Finally, a QCD motivated calculation [7] predicts too large a cross section for $W_{\gamma\gamma} \geqslant 1.8$ GeV/c^2.

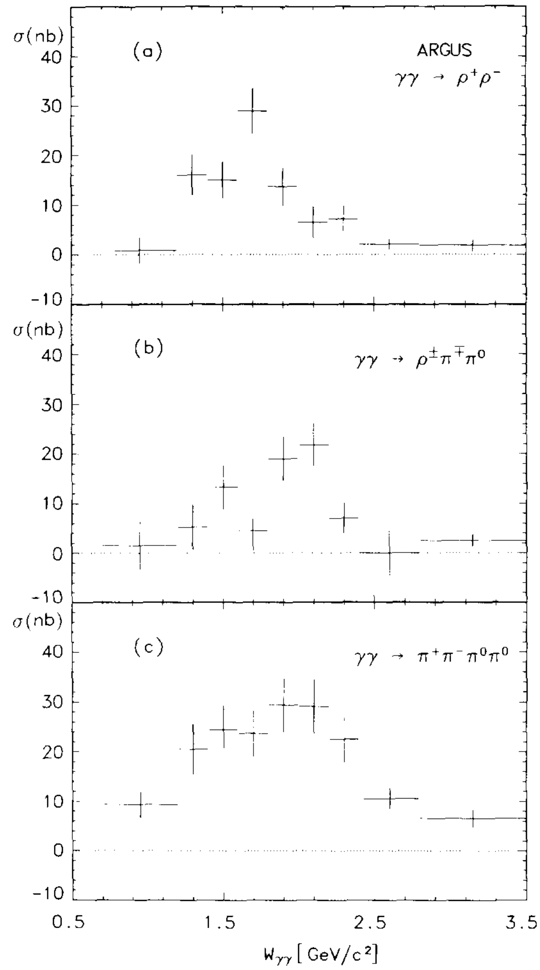

Fig. 4. Cross sections versus $W_{\gamma\gamma}$ as derived from the fit. (a) $\gamma\gamma\to\rho^+\rho^-$; (b) $\gamma\gamma\to\rho^\pm\pi^\mp\pi^0$; (c) non-resonant $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$.

In conclusion, the reaction $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$ has been investigated. The cross section for the reaction

$\gamma\gamma \to \rho^+\rho^-$ is suppressed by about a factor of four compared with the cross section for $\gamma\gamma \to \rho^0\rho^0$.

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