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Two-photon production of final states with a $p\bar{p}$ pair

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Abstract. Two-photon production of the exclusive final states $p\bar{p}+n\pi$ ($n=0$, 1, 2, and 3) has been investigated using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The reactions $\gamma\gamma\to p\bar{p}\pi^0$ and $\gamma\gamma\to p\bar{p}\pi^+\pi^-\pi^0$ have been observed for the first time, as have the Δ^{++} and $\overline{\Delta^{++}}$ baryons in the final state $p\bar{p}\pi^+\pi^-$. No evidence was found for $\Delta^{++}\overline{\Delta^{++}}$ production. Topological cross sections for two-photon production of $p\bar{p}$, $p\bar{p}\pi^0$, $p\bar{p}\pi^+\pi^-$ and $p\bar{p}\pi^+\pi^-\pi^0$, as well as the cross section for $\gamma\gamma\to\Delta^{++}\bar{p}\pi^-$ + c.c., have been measured. Upper limits are given for the cross sections for $\gamma\gamma\to\Delta^0\overline{\Delta^0}$, $\gamma\gamma\to\Delta^{++}\overline{\Delta^{++}}$ and $\gamma\gamma\to\Lambda\bar{\Lambda}$.

1 Introduction

Two-photon production of four exclusive final states with a $p\bar{p}$ pair accompanied by up to three pions, $e^+e^-\to e^+e^-p\bar{p}+n\pi$ ($n=0$, 1, 2, and 3), has been studied:

$$\gamma\gamma\to p\bar{p} \quad (1)$$

$$\gamma\gamma\to p\bar{p}\pi^0 \quad (2)$$

$$\gamma\gamma\to p\bar{p}\pi^+\pi^- \quad (3)$$

$$\gamma\gamma\to p\bar{p}\pi^+\pi^-\pi^0. \quad (4)$$

Reactions (2) and (4) have been observed for the first time while the other two have previously been seen by other groups ($p\bar{p}$: [1–3]; and $p\bar{p}\pi^+\pi^-$: [4]). This report also presents the first evidence for $\Delta^{++}\bar{p}\pi^-$ + c.c. production using reaction (3).

Available model calculations of the cross sections for baryon anti-baryon production in two-photon interactions are based on perturbative QCD [5]. One approach [6] uses both asymptotic wave functions and, for $\gamma\gamma\to p\bar{p}$, wave functions based on QCD sum rules [7]. Another approach treats a baryon as composed of a quark and a diquark [8].

It should be noted that the QCD calculations might be valid only for large momentum transfers, $t\geqq 5$ (GeV/c)^2. This experiment is sensitive to momentum transfers $t\leqq 2.5$ (GeV/c)^2, which holds approximately for previous results as well. The validity to compare the present data with the model calculations is therefore uncertain.

2 Data and event selection

The data used for the investigations reported here correspond to an integrated luminosity of 234 pb^{-1}, and were collected using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The beam energies varied between 4.7 and 5.3 GeV. ARGUS is a universal magnetic detector with cylindrical symmetry [9]. The dE/dx and time-of-flight measurements allow excellent identification of the rather slow charged particles produced in two-photon interactions at the DORIS II beam energies. The high sensitivity and large acceptance of the electromagnetic calorimeter allow an efficient detection of photons. The frequent annihilation of anti-protons in the calorimeter was also used for a consistency check of the anti-proton identification. The trigger which is sensitive to events from two-photon collisions basically required two charged particles with transverse momenta larger than 125 MeV/c.

Candidate events for the reactions (1) to (4) were selected requiring two oppositely charged particles originating from a common event vertex and identified as a $p\bar{p}$ pair with likelihood ratios exceeding 5%. All other particle hypotheses ($e^\pm$, $\mu^\pm$, $\pi^\pm$, and $K^\pm$) had to have likelihood ratios less than 5%. For reactions (3) and (4) an additional $\pi^+\pi^-$ pair was required, also originating from the main event vertex, and both particles being identified as pions with likelihood ratios exceeding 5%. Clear unambigous particle identification is obtained in each case. Background from τ-pair events is obviously excluded due to the presence of a well identified $p\bar{p}$ pair.

For reactions (2) and (4), exactly two photons were required, a photon being identified as an energy cluster of more than 50 MeV deposited in the electromagnetic calorimeter and well separated from a charged particle trajectory. For reactions (1) and (3) no such energy cluster was allowed.

The invariant mass distributions of the two detected photons for reactions (2) and (4) are shown in Fig. 1a and b respectively (with the additional two-photon interaction selection criteria described below). Each mass spectrum was fitted using a gaussian for the π^0 signal with fixed mass and width, plus a constant background term. The number of fitted π^0 mesons was 10.2 ± 4.0 and 18.5 ± 5.1 in the two cases respectively. Events were selected if the invariant mass of the two photons was in the range between 60 and 220 MeV/c^2. A constrained fit to the π^0 mass was performed.

No other activity was allowed in the detector. This assured that the e^+ and e^- beam particles in two-photon events were scattered at very small angles (the so called "no-tag" condition), which favours the collisions between two transversely polarized photons.

To enhance two-photon events, the scalar sum of the individual particle momenta, $\sum|\mathbf{p}_i|$, had to be less than 3 GeV/c for reactions (1) and (2), and less than 3.5 GeV/c for the remaining reactions. The resulting p_T^2 distributions of the event candidates for

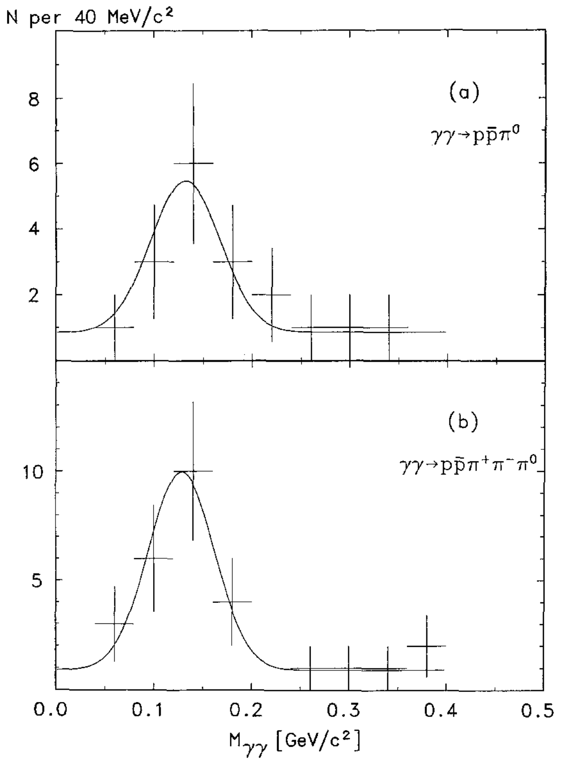

Fig. 1 a, b. Invariant mass distributions of the two detected photons in event candidates for the reactions (2) and (3): **a** $\gamma\gamma \to p\bar{p}\pi^0$ and **b** $\gamma\gamma \to p\bar{p}\pi^+\pi^-\pi^0$. The curves are the results of fitting a gaussian function plus a constant background term

reactions (1) to (4) are shown in Fig. 2a to d, where p_T is the total transverse momentum of the final state particles i, $p_T = |\sum \mathbf{p}_{T,i}|$. The p_T^2 distribution of exclusive events is expected to be strongly enhanced close to zero. This is clearly demonstrated by the data. The background due to non-exclusive events is expected to be distributed uniformly in p_T^2 for small values of p_T^2. Each p_T^2 distribution was fitted with an expression derived from Monte Carlo simulations (see Sect. 3) plus a constant background term. The results of the fits are shown as solid lines in Fig. 2a to d. In each case the background level is compatible with zero. To assure as small a background contamination as possible together with a significant event sample, cuts in p_T were applied leading to the final event samples given in Table 1. Note that the number of events se-

Table 1. Total number of events (N) for reactions (1) to (4) after imposing all cuts

Reaction	N(events)	N(background)	p_T (GeV/c) cut
(1) $\gamma\gamma \to p\bar{p}$	60	0.5 ± 0.3	$p_T \leqq 0.1$
(2) $\gamma\gamma \to p\bar{p}\pi^0$	16	0.2 ± 0.3	$p_T \leqq 0.1$
(3) $\gamma\gamma \to p\bar{p}\pi^+\pi^-$	62	0.0 ± 3.0	$p_T \leqq 0.3$
(4) $\gamma\gamma \to p\bar{p}\pi^+\pi^-\pi^0$	19	1.4 ± 2.8	$p_T \leqq 0.3$

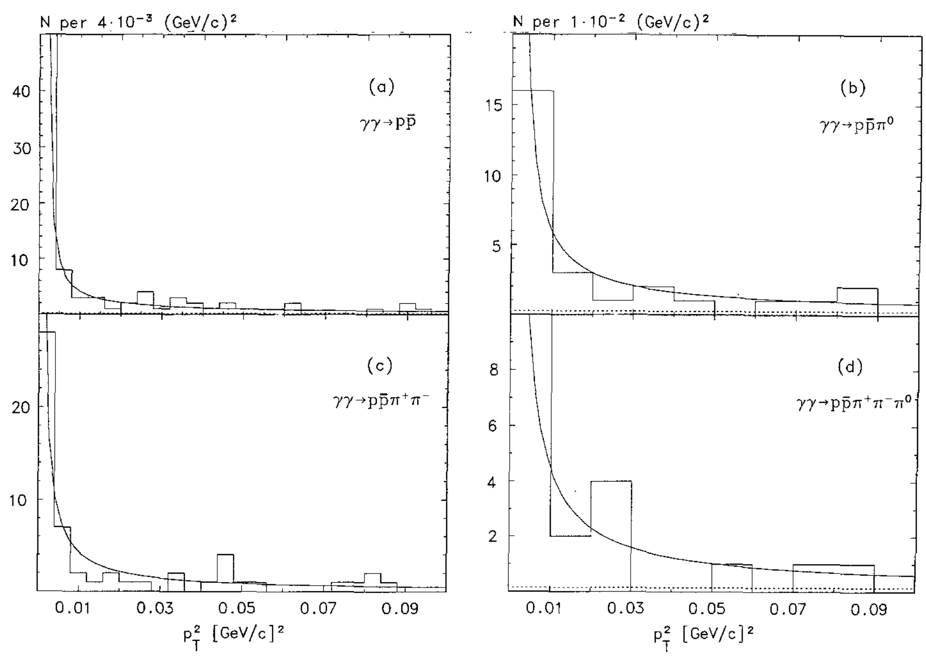

Fig. 2a–d. p_T^2 distributions for event candidates for the reactions (1) to (4): **a** $\gamma\gamma \to p\bar{p}$, **b** $\gamma\gamma \to p\bar{p}\pi^0$, **c** $\gamma\gamma \to p\bar{p}\pi^+\pi^-$, and **d** $\gamma\gamma \to p\bar{p}\pi^+\pi^-\pi^0$. The curves (full line) are the results from fitting a function derived from Monte Carlo, plus a constant background term. The backgrounds (broken line) are shown separately

lected for reactions (2) and (4) agree within errors with the respective number of fitted π^0 mesons.

3 Acceptance calculations

A Monte Carlo program was used to simulate interactions of two transversely polarized photons with exact luminosity functions [10]. The events were generated with a constant two-photon cross section. Isotropic phase-space was used to simulate the final states $p\bar{p}$, $p\bar{p}\pi^+\pi^-$, $\Delta\Delta$ and $\Delta p\pi$. No account was taken of possible spin effects in final states containing a Δ. Each Monte Carlo data set was generated with a beam energy distribution identical to that of the data. The Monte Carlo events were passed through a detector simulation, and were reconstructed and selected using the same programs as for the data. The trigger simulation used thresholds for the detector components as determined from the data. The variation in actual trigger conditions was also taken into account.

Since no search was made for $\Lambda\bar{\Lambda}$ events with separate decay vertices, the $p\bar{p}\pi^+\pi^-$ sample was used for this final state. It is known from other ARGUS studies [11] that about 50% of all Λ baryons decaying into $p\pi$ are fitted to the main event vertex. The acceptance for final states with a π^0 was calculated using the purely charged $p\bar{p}$ and $p\bar{p}\pi^+\pi^-$ generated events, correcting for the π^0 efficiency, which is known from our studies of other two-photon reactions, together with a proper scaling of the threshold region.

The derived sensitivities, expressed as number of detected events per nanobarn of the two-photon cross section and per 100 MeV/c^2 of $W_{\gamma\gamma}$, are about 3 for $\gamma\gamma\to p\bar{p}$ and 2 for the other purely charged channels, except for $\Lambda\bar{\Lambda}$ which is about 0.5. $W_{\gamma\gamma}$ denotes the invariant mass of the two colliding photons or, equivalently, the invariant mass of the detected final state. The channels including a π^0 have sensitivities which are about 50% lower than those for the corresponding purely charged channels. The systematic uncertainty in the derived sensitivities is the same for all reactions considered, $\pm 13\%$. It is composed of the contributions from event generation and detector simulation ($\pm 10\%$), experimental luminosity ($\pm 5\%$), and trigger simulation ($\pm 5\%$).

4 Results

The differential cross section $d\sigma/d\cos\theta_p^*$ for reaction (1), $\gamma\gamma\to p\bar{p}$, is shown in Fig. 3. θ_p^* denotes the proton production angle, in the center-of-mass system of the colliding photons, with respect to the direction of one of the incoming photons. In the analysis this direction was represented by that of the incoming e^+ beam,

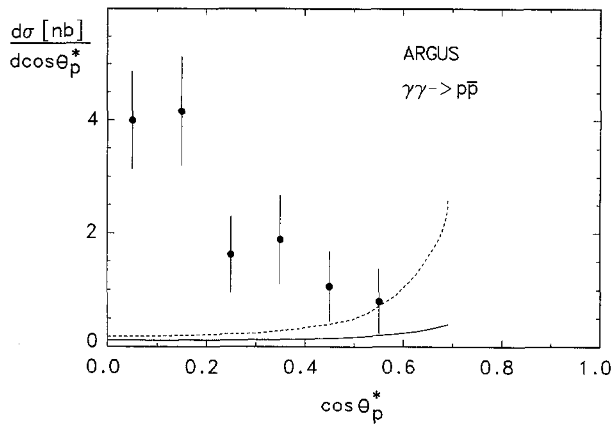

Fig. 3. Differential cross section $d\sigma/d\cos\theta_p^*$, where θ_p^* is the proton production angle in the center-of-mass system of the colliding photons. The systematic error of $\pm 13\%$ is not shown. The prediction [6] using wave functions [7] based on QCD sum rules is shown (for $W_{\gamma\gamma}=2.4$ GeV/c^2) as a solid line curve and that by a diquark model [8] (for $W_{\gamma\gamma}=2.6$ GeV/c^2) as a broken line curve. The mean $W_{\gamma\gamma}$ of the data is 2.3 GeV/c^2

which is a good approximation due to the properties of bremsstrahlung processes. The Monte Carlo $p\bar{p}$ events were generated uniformly in $\cos\theta_p^*$ between 0 and 1. The acceptance is zero for $\cos\theta_p^* > 0.6$.

The model calculations [6, 8] for the $p\bar{p}$ cross section are also shown in Fig. 3. In both models is the cross section expected to rise with increasing $\cos\theta_p^*$, and to be strongly peaked at $\cos\theta_p^*$ close to 1. The latter cannot be verified due to the limited acceptance. In the accessible range of $\cos\theta_p^*$, however, both models underestimate the cross section. More importantly and in contrast to the predictions, the measured $\cos\theta_p^*$ distribution is enhanced at θ_p^* near 90°. This was also observed by JADE [2].

The topological cross sections for the four reactions are shown in Figs. 4 and 5 respectively. Note that the cross section for $\gamma\gamma\to p\bar{p}$ is given for the range $\cos\theta_p^* \leqq 0.6$, since the acceptance is limited to that range. This is the first time the cross sections for reactions (2) and (4) have been measured. No significant structure is visible. The cross section for reaction (1) agree well with previous measurements [1–3], as does the topological cross section for reaction (3) [4].

The final state $p\bar{p}\pi^+\pi^-$ was also used to study production of Λ and Δ baryons. The invariant mass distribution of doubly charged (neutral) $p\pi$ combinations is shown in Fig. 6a (6b). Δ production was estimated by fitting the data with a linear combination of $p\pi$ phase-space and $\Delta\to p\pi$ mass distributions. The $p\pi$ phase-space and the Δ mass distributions were derived from Monte Carlo simulations of $\gamma\gamma\to p\bar{p}\pi^+\pi^-$ and $\gamma\gamma\to\Delta^{++}\bar{p}\pi^-$ + c.c. events respectively. In both cases were the $p\bar{p}\pi^+\pi^-$ invariant mass

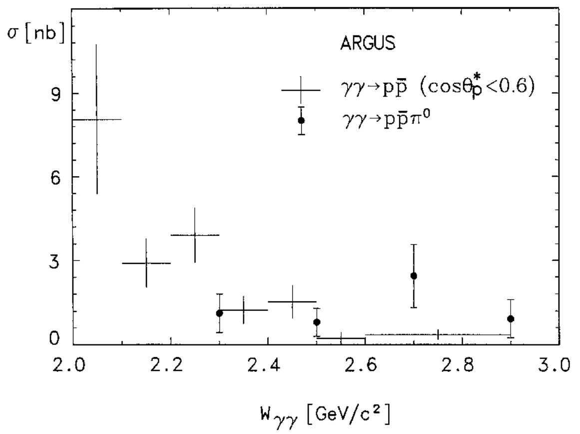

Fig. 4. Topological cross sections versus $W_{\gamma\gamma}$ for reaction (1), $\gamma\gamma\to p\bar{p}$ ($\cos\theta_p^*\leqq 0.6$), and reaction (2), $\gamma\gamma\to p\bar{p}\pi^0$. The systematic errors of $\pm 13\%$ are not shown

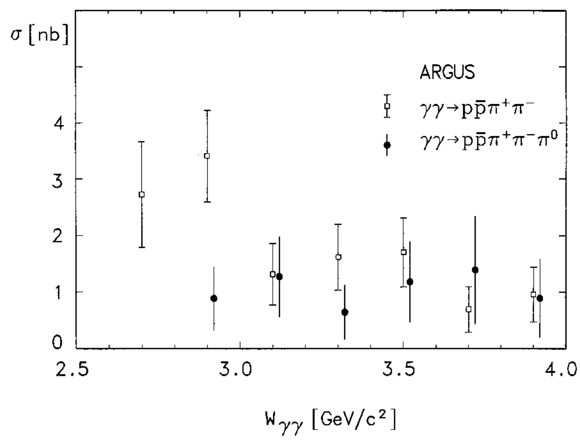

Fig. 5. Topological cross sections versus $W_{\gamma\gamma}$ for reaction (3), $\gamma\gamma\to p\bar{p}\pi^+\pi^-$, and reaction (4), $\gamma\gamma\to p\bar{p}\pi^+\pi^-\pi^0$. The systematic errors of $\pm 13\%$ are not shown

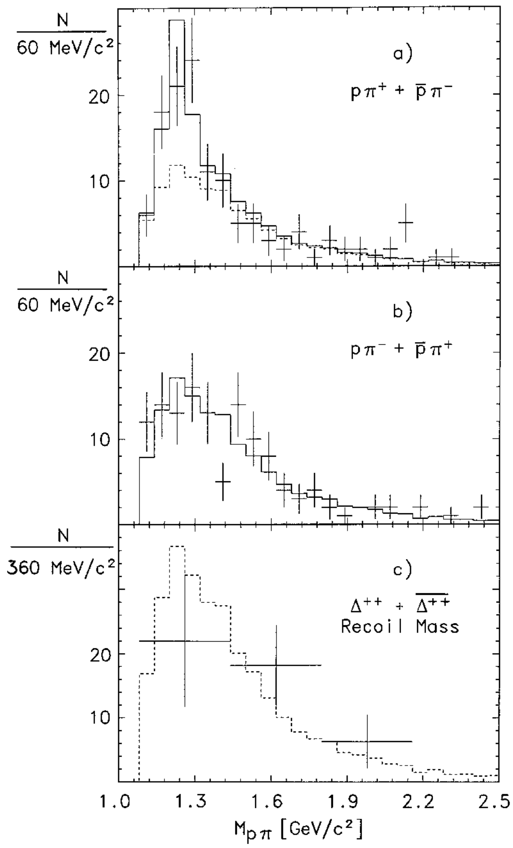

Fig. 6a–c. Invariant $p\pi$ mass distributions in the $p\bar{p}\pi^+\pi^-$ events. **a** Doubly charged $p\pi$ combinations, and **b** neutral $p\pi$ combinations. The data are shown with error bars, and the fitted mass distributions as histograms (full line). In **a** the phase-space contribution is shown separately (broken line). **c** $p\pi$ combination recoiling against a Δ^{++} or a $\overline{\Delta^{++}}$. Data are shown with error bars, the $p\pi$ phase-space spectrum is overlayed as a histogram

Table 2. Number (N) of found Δ baryons in the $\gamma\gamma\to p\bar{p}\pi^+\pi^-$ events

Resonance	N	χ^2/Ndf	$\Delta N(1\sigma)$	N(95% C.L.)
Δ^{++} or $\overline{\Delta^{++}}$	40.2	10.5/17	± 11.4	–
Δ^0 or $\overline{\Delta^0}$	0.0	23.2/17	–	$\leqq 20.9$

distributions reweighted to agree in shape with the corresponding distribution in the data. The Δ was parametrized by a relativistic Breit-Wigner function with mass and width of 1.232 and 0.115 GeV/c^2 respectively.

The $p\pi$ mass distributions resulting from the fits are also shown in Fig. 6a and b. Clear signals for doubly charged Δ are seen but no neutral Δ. This is the first observation of doubly charged Δ production in two-photon interactions. The Δ fit results are summarized in Table 2.

To determine whether the doubly charged Δ baryons are correlated, the invariant mass spectrum of the $p\pi$ pair recoiling against a Δ^{++} or against a $\overline{\Delta^{++}}$ was studied. The Δ recoil mass spectrum was determined by fitting the sum of the $p\pi^+$ mass spectrum in intervals of the $\bar{p}\pi^-$ mass, and of the $\bar{p}\pi^-$ mass spectrum in intervals of the $p\pi^+$ mass. The fit used, identically to the above determination of the number of single Δ baryons, a linear combination of $p\pi$ phase-space and a Breit-Wigner shape for the Δ. The resulting Δ recoil mass spectrum is shown in Fig. 6c, and was in turn fitted using again a combination of phase-space and a Δ shape. The $p\pi$ phase-space spectrum is overlayed as a histogram in Fig. 6c.

The presence of $\Delta^{++}\overline{\Delta^{++}}$ events should show up as a Δ signal with two entries per event on top of

Table 3. Number (N) of found baryon anti-baryon events in the final state $p\bar{p}\pi^+\pi^-$

Final State	N	N (95% C.L.)	χ^2/Ndf	Method
$\Delta^{++}\overline{\Delta^{++}}$	0	$\leqq 12.3$	1.5/1	χ^2 (Fig. 6c)
$\Delta^0\overline{\Delta^0}$	0	$\leqq 10.5$	23.2/17	χ^2 (Fig. 6b)
$\Lambda\bar{\Lambda}$	1	$\leqq 4.8$	–	Poisson

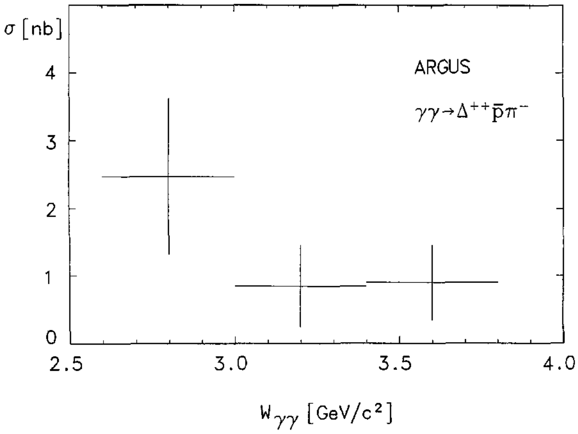

Fig. 7. Cross section for $\gamma\gamma \to \Delta^{++}\bar{p}\pi^- +$c.c. versus $W_{\gamma\gamma}$. The systematic errors of $\pm 13\%$ are not shown

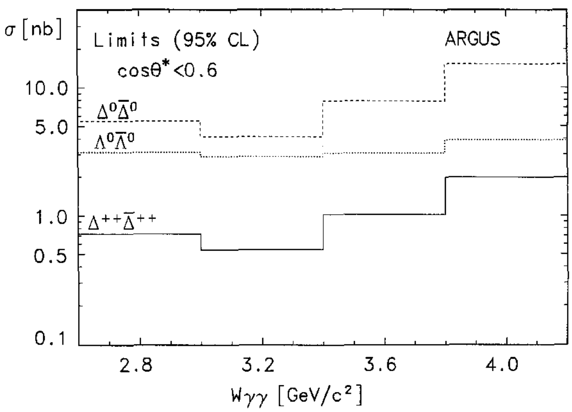

Fig. 8. Upper limits at the 95% C.L. versus $W_{\gamma\gamma}$ ($\cos\theta^* \leqq 0.6$) for the cross sections for $\gamma\gamma \to \Delta^0\overline{\Delta^0}$ (broken line), $\gamma\gamma \to \Lambda\bar{\Lambda}$ (dotted line), and $\gamma\gamma \to \Delta^{++}\overline{\Delta^{++}}$ (full line)

the $p\pi$ phase-space distribution from $\Delta p\pi$ events. No evidence for $\gamma\gamma \to \Delta^{++}\overline{\Delta^{++}}$ was found, and the result from the fit is presented in Table 3. The events containing a Δ^{++} or a $\overline{\Delta^{++}}$ are therefore due to the reaction $\gamma\gamma \to \Delta^{++}\bar{p}\pi^- +$c.c., which constitutes a sizeable fraction ($\sim 65\%$) of the $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ events. The cross section for this reaction is shown in Fig. 7.

$\gamma\gamma \to \Lambda\bar{\Lambda}$ events were searched for by requiring both the $p\pi^-$ and the $\bar{p}\pi^+$ combination to have an invariant mass between 1.10 and 1.13 GeV/c^2. This interval is more than five times larger than the experimental Λ mass resolution. One candidate was found.

Table 3 summarizes the search for baryon anti-baryon production, and the upper limits for the respective cross sections are shown in Fig. 8. These constitute an improvement by about a factor two of previous results [4]. Similarly to the case for the $p\bar{p}$ cross section, the upper limits are given for $\cos\theta^* \leqq 0.6$, where θ^* is the baryon production angle in the $\gamma\gamma$ center-of-mass system. Note also that the $p\bar{p}\pi^+\pi^-$ final state covers all the $\Delta^{++}\overline{\Delta^{++}}$ decay modes, but only 1/9 of the $\Delta^0\overline{\Delta^0}$ decay modes.

5 Summary of the results

Two-photon production of four final states with a $p\bar{p}$ pair accompanied by up to three pions, $e^+e^- \to e^+e^- p\bar{p} + n\pi$ ($n = 0$, 1, 2, and 3), has been studied. This is the first time two-photon interactions leading to the final states $p\bar{p}\pi^0$, $p\bar{p}\pi^+\pi^-\pi^0$ and $\Delta^{++}\bar{p}\pi^- +$c.c.$\to p\bar{p}\pi^+\pi^-$ have been measured.

No events of the type $\gamma\gamma \to \Delta^{++}\overline{\Delta^{++}}$ were found. The upper limit for the ratio $\sigma(\gamma\gamma \to \Delta^{++}\overline{\Delta^{++}})/\sigma(\gamma\gamma \to p\bar{p})$ is found to be 1 at the 95% C.L. in the range $2.6 \leqq W_{\gamma\gamma} \leqq 3.0$ and for $\cos\theta^* \leqq 0.6$. This is well above the prediction of 0.1 by a diquark model [8]. The naive expectation for the ratio being equal to $(\text{charge}(\Delta^{++})/\text{charge}(\text{proton}))^4 = 16$ is certainly in disagreement with the data. The same holds for the prediction of about 50 [6] using only asymptotic wave functions.

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