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M.Althoff, W.Braunschweig, F.J.Kirschfink, K.Lübelsmeyer, H.-U.Martyn,
J.Rimkus[#], P.Rosskamp, H.G.Sander[##], D.Schmitz, H.Siebke, W.Wallraff
I.Physikalisches Institut der RWTH Aachen, Germany [$]

H.M.Fischer, H.Hartmann, A.Jocksch, G.Knop, L.Köpke[###], H.Kolanoski,
H.Kück, V.Mertens, R.Wedemeyer, M.Wollstadt[####],
Physikalisches Institut der Universität Bonn, Germany [$]

Y.Eisenberg[#####], A.Eskreys[*], K.Gather, H.Hultschig, P.Joos, U.Kötz,
H.Kowalski, A.Ladage, B.Löhr, D.Lüke, P.Mättig, D.Notz, R.J.Nowak[**], J.Pyrlik,
M.Rushton, W.Schütte, D.Trines, T.Tymieniecka[**], 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, K.U.Posnecker, B.H.Wiik
II.Institut für Experimentalphysik der Universität Hamburg, Germany [$]

R.Beuselinck, D.M.Binnie, A.J.Campbell[****], P.J.Dornan, B.Foster, D.A.Garbutt, C.Jenkins,
T.D.Jones, W.G.Jones, J.McCardle, J.K.Sedgbeer, J.Thomas, W.A.T. Wan Abdullah[*****]
Department of Physics, Imperial College London, England [$$]

K.W.Bell, M.G.Bowler, P.Bull, R.J.Cashmore, P.E.L.Clarke, R.Devenish,
P.Grossmann, C.M.Hawkes, S.L.Lloyd, G.L.Salmon, C.Youngman
Department of Nuclear Physics, Oxford University, England [$$]

G.E.Forden, J.C.Hart, J.Harvey, D.K.Hasell, J.Proudfoot[+], D.H.Saxon
Rutherford Appleton Laboratory, Chilton, England [$$]

F.Barreiro, M.Dittmar, M.Holder, G.Kreutz, B.Neumann
Fachbereich Physik der Universität-Gesamthochschule Siegen, Germany [$]

E.Duchovni, U.Karshon, G.Mikenberg, R.Mir, D.Revel, E.Ronat, A.Shapira, G.Yekutieli
Weizmann Institute, Rehovot, Israel [$$$]

G.Baranko, T.Barklow[++], A.Caldwell, M.Cherney, J.M.Izen, M.Mermikides, G.Rudolph,
D.Strom, M.Takashima, H.Venkataramania, E.Wicklund, Sau Lan Wu, G.Zobernig
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA [$$$$]

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#	Now at Siemens, München, Germany
##	Now at CERN, Geneva, Switzerland
###	Now at University of California, Santa Cruz, CA, USA
####	Now at Lufthansa, Frankfurt, Germany
#####	On leave from Weizmann Institute, Rehovot, Israel
*	On leave from Cracow University, Poland
**	On leave from Warsaw University, Poland
***	On leave from University of Science and Technology of China, Hefei, Supported by the Konrad-Adenauer-Stiftung
****	Now at Glasgow University, Glasgow, UK
*****	On leave from Universiti Malaya, Kuala Lumpur
+	Now at Argonne National Laboratory, Argonne, IL, USA
++	Now at SLAC, Stanford, CA, USA
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Abstract

Production of the $p\bar{p}\pi^+\pi^-$ final state by two photon scattering was observed. The cross section for $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ was determined assuming phase space production. No evidence was found for the production or formation of resonances. Upper limits are given for Λ and Δ pair production, for production of $p\bar{p}\rho^0$ and for the two photon excitation of $c\bar{c}$ bound states.

Exclusive production of hadron pairs in two photon collisions at large momentum transfer may be dominated by the pointlike coupling of the photons to the quarks. Within the framework of perturbative QCD cross sections for two photon production of meson pairs at large momentum transfer have been calculated /1/ and were found to agree reasonably well with a recent measurement /2/. Similar calculations have been done for $p\bar{p}$ production in Ref. /3/ and more generally for baryon pairs in Ref. /4/. However, the two theoretical predictions for $\gamma\gamma \to p\bar{p}$ differ by roughly two orders of magnitude and disagree with the experimental data /5, 6/. In this paper we report on a search for two photon production of $\Lambda\bar{\Lambda}$, $\Delta^{++}\overline{\Delta^{++}}$ and $\Delta^{0}\overline{\Delta^{0}}$ pairs in events of the type $e^+e^- \to e^+e^-\ p\bar{p}\pi^+\pi^-$. We have also looked for $p\bar{p}\rho^0$ production and for the two photon excitation of $c\bar{c}$ bound states.

The experiment was performed with the TASSO detector at the DESY storage ring PETRA. A description of the detector can be found elsewhere /7/. The data correspond to an integrated luminosity of 74 pb^{-1} at an average beam energy of 16.95 GeV. The trigger imposed one of the following requirements /8/: i) at least two charged particles with associated signals in inner time-of-flight (TOF) counters separated by more than 154° in azimuth, or ii) two or more charged particles originating from the interaction region within $z \sim \pm 15$ cm along the beamline, or iii) four or more charged particles. The charged particle tracks were found in the central chambers by a hardware processor, whose track finding efficiency depends on the momentum component $|\vec{p}_\perp|$ 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 events with four charged particles (four prongs) produced in two photon collisions were selected by requiring exactly four charged particle tracks with net charge zero. The polar angles Θ of the tracks with respect to the beam axis were restricted to $|\cos\Theta| \leq 0.8$ and the transverse momenta had to be larger than $|\vec{p}_\perp| \geq 0.1$ GeV/c. Photon-photon events with unobserved particles were rejected by demanding the vector sum of the transverse momenta of the four particles ($|\sum\vec{p}_\perp|$) to be less than 0.14 GeV/c. This cut effectively restricts the average of the four momentum transfer squared of the photons to less than about 0.01 GeV^2. For particle identification we used the TOF-measurements provided by the 48 scintillation counters surrounding the cylindrical drift chamber. To obtain efficient separation of pions, kaons and protons the momentum of each track had to be less than 1.6 GeV/c. These cuts also reduce background from one photon annihilation processes. The remaining contribution of the one photon channel was estimated to be negligible.

For each event selected by these cuts the squares of the masses for the individual particles (m_{TOF}^2) were computed from their measured track lengths, momenta and TOF values. To find $p\bar{p}\pi^+\pi^-$ events, we first searched for events with $p\bar{p}$ pairs. In Fig. 1a we show the larger m_{TOF}^2 of the two positively charged particles plotted versus the larger m_{TOF}^2 of the two negatively charged particles. There is a well separated cluster of $p\bar{p}$ pairs. We selected $p\bar{p}$ candidates by requiring $m_{TOF}^2 \geq 0.4$ GeV^2 for both particles in Fig. 1a. For their tracks we calculated the TOF assuming the particles are protons. The difference Δt between the calculated TOF and the measured TOF was required to be $|\Delta t| \leq 3\sigma$, where σ is the r.m.s. resolution of Δt. For the 15 events with $p\bar{p}$ candidates satisfying these cuts we then considered the particle pair not identified as $p\bar{p}$. In Fig. 1b we show the m_{TOF}^2 of the positively charged track versus the m_{TOF}^2 of the negatively charged track for these pairs. Both particles of each pair cluster at $m_{TOF}^2 = m_\pi^2$, indicating that the 15 events are due to the reaction $\gamma\gamma \to p\bar{p}\pi^+\pi^-$. No candidates for the reaction $\gamma\gamma \to p\bar{p}p\bar{p}$ were found. A contamination of the pion sample and of the proton sample by K^+K^- pairs was estimated to be negligible. We checked that none of the $\pi^+\pi^-$ pairs was faked by an e^+e^- pair from the conversion of a photon.

To demonstrate that these events are exclusively produced $p\bar{p}\pi^+\pi^-$ final states we show in Fig. 1c the distribution of the squared vector sum of the transverse momenta of the four tracks without the transverse momentum balance cut. The distribution peaks at zero as expected for $\gamma\gamma$-events with no missing particles. The $|\sum\vec{p}_\perp|^2$-distribution of the data was compared to the shape of the corresponding distribution obtained from a Monte Carlo simulation of $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ events assuming a phase space like production mechanism (see histogram in Fig. 1c). The Monte Carlo distribution describes the behaviour of the data well. A background contribution from events with missing particles is expected to have a flat distribution in $|\sum\vec{p}_\perp|^2$. This background contribution was estimated from the plot in Fig. 1c to be less than 0.5 events in the range $|\sum\vec{p}_\perp| < 0.14$ GeV/c. The cut in $|\sum\vec{p}_\perp|$ removed one event. Beam-gas reactions contribute less than 0.5 events. In total we estimated a background of one event among the 15 $p\bar{p}\pi^+\pi^-$ events. The uncorrected distribution of the center of mass energy $W_{\gamma\gamma}$ of the $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ events is given in Fig. 2a.

The detection efficiency was determined by a Monte Carlo simulation of the reaction $e^+e^- \to e^+e^-\ p\bar{p}\pi^+\pi^-$ in the detector. Events were generated according to

$$\frac{d\sigma_{e^+e^- \to e^+e^-\ p\bar{p}\pi^+\pi^-}}{dW_{\gamma\gamma}\,d\omega\,d\xi} = \frac{dL(W_{\gamma\gamma},\omega)}{dW_{\gamma\gamma}\,d\omega} \cdot \frac{d\sigma_{\gamma\gamma \to p\bar{p}\pi^+\pi^-}(W_{\gamma\gamma},\xi)}{d\xi}$$

where ω represents the kinematical variables of the two-photon system other than $W_{\gamma\gamma}$ and ξ represents the kinematical variables of the $p\bar{p}\pi^+\pi^-$ final state. $L(W_{\gamma\gamma},\omega)$ is the luminosity function for transverse photons /9/. Since the detection efficiency depends on the mechanism leading to the $p\bar{p}\pi^+\pi^-$ final state, different models for $d\sigma/d\xi$ were considered: a) baryon pair production, b) $p\bar{p}\rho^\circ$ production, c) production of $c\bar{c}$ bound states and d) production according to $p\bar{p}\pi^+\pi^-$ phase space. In the case of baryon pair production the baryons were generated with a flat $\cos\Theta^*$ distribution, where Θ^* is the production angle in the $\gamma\gamma$ c. m. system. The differential cross section $d\sigma/d\cos\Theta^*$ was taken to be independent of $W_{\gamma\gamma}$ and the baryons were assumed to decay isotropically in their rest system.

The simulation of the detector included energy loss, multiple scattering, nuclear interactions and the detector efficiencies and resolutions. The generated events had to fulfil the same cuts as described above. The detection efficiency for $\gamma\gamma\to p\bar{p}\pi^+\pi^-$ is given in Fig. 2a for phase space production and for production via $\Lambda\bar{\Lambda}$ pairs. The rise above threshold is caused by the $p_\perp$ dependence of the trigger efficiency, while the decrease toward higher $W_{\gamma\gamma}$ is due to the upper momentum cut. The error in the determination of the detector acceptance is dominated by the uncertainties in the energy loss and nuclear interactions for low $W_{\gamma\gamma}$ and by the two photon luminosity at large $W_{\gamma\gamma}$. It is ~20% for $W_{\gamma\gamma}$ between 2.5 and 3.0 GeV and decreases to less than ~12% above $W_{\gamma\gamma}$=3.0 GeV.

To study the exclusive production of baryon pairs ($\gamma\gamma\to\Lambda\bar{\Lambda}$, $\Delta^{++}\overline{\Delta^{++}}$, $\Delta^\circ\overline{\Delta^\circ}$) we plot in Fig. 2b (2c) the invariant mass of the $p\pi^-$ ($p\pi^+$) -system versus the invariant mass of the $\bar{p}\pi^+$ ($\bar{p}\pi^-$) -system. In Fig. 2b we looked for $\Lambda\bar{\Lambda}$ pairs. The mass resolution σ_m was determined by the Monte Carlo simulation. No event was found in the Λ mass region defined by $m_{p\pi} \leqq m_\Lambda+3\sigma_m$ = 1.160 GeV in Fig. 2b. We searched for $\Delta\bar{\Delta}$ pairs in Figures 2b and 2c. There was also no evidence for exclusive $\Delta\bar{\Delta}$ pair production. Defining the Δ mass range as $m_{p\pi} \leqq$ 1.4 GeV we found 4 (3) events in the $\Delta^{++}\overline{\Delta^{++}}$ ($\Delta^\circ\overline{\Delta^\circ}$) region. Assuming $p\bar{p}\pi^+\pi^-$ phase space production and extrapolating the event yield into the $\Delta\bar{\Delta}$ region, 5.4±2.7 (5.6±2.7) events are expected in the $\Delta^{++}\overline{\Delta^{++}}$ ($\Delta^\circ\overline{\Delta^\circ}$) region. Since no signal from the production of $\Lambda\bar{\Lambda}$, $\Delta^{++}\overline{\Delta^{++}}$ and $\Delta^\circ\overline{\Delta^\circ}$ was found we derived upper limits (95% c. l.) on the cross sections from the observed numbers of events. In Fig. 3a the upper limits on the differential cross sections integrated over the angular range $|\cos\Theta^*|\leqq 0.6$ are given. The $\Lambda\bar{\Lambda}$ and $\Delta^\circ\overline{\Delta^\circ}$ cross sections are corrected for the unseen Λ and Δ° decay modes.

Since photons couple to the electric charge one could expect the cross section for $\gamma\gamma\to\Delta^{++}\overline{\Delta^{++}}$ to be larger than for $\gamma\gamma\to p\bar{p}$. The theoretical calculation of Ref. /4/ gives cross section ratios between 10 to 14 in the limit of high momentum transfer. Assuming a cross section ratio of 10 and using our measured cross section for $\gamma\gamma\to p\bar{p}$ of Ref. /6/ we should find 18.7 events for $\gamma\gamma\to\Delta^{++}\overline{\Delta^{++}}$ in the $W_{\gamma\gamma}$ range from 2.5 to 3.0 GeV in contrast to the measured upper limit (95% c. l.) of 4.7 events.

We also searched for $p\bar{p}\rho^\circ$ production. In the ρ° region (invariant masses of the $\pi^+\pi^-$-system between 0.60 and 0.95 GeV) 5 events were found. This is consistent with the number of events expected for phase space production of the $p\bar{p}\pi^+\pi^-$ final state. From the number of observed events in the ρ° region we derived upper limits on $p\bar{p}\rho^\circ$ production. The cross section is smaller than 3.2 nb for the $W_{\gamma\gamma}$ range 2.5 to 3.0 GeV and smaller than 1.8 nb for 3.0 to 4.5 GeV with 95% confidence.

Since 14 of the 15 events have c. m. energies between 2.8 and 3.6 GeV (see Fig. 2a) a search was made for the two photon excitation of $c\bar{c}$ bound states. The lightest $c\bar{c}$ states with positive C-parity which couple to two real photons are the $\eta_c(2984)$, $\chi(3415)$ and $\chi(3555)$. No evidence for two photon excitation of any of these resonances was found. The yields of events within a $2\sigma_m$-interval around the nominal masses are consistent with a flat distribution between 2.8 and 3.6 GeV. From the observed numbers of events upper limits (95% c. l.) were derived on the products of the $\gamma\gamma$-width times the decay branching ratio into the $p\bar{p}\pi^+\pi^-$ final state. For the calculation of the detection efficiency the decay particles were generated according to $p\bar{p}\pi^+\pi^-$ phase space. The resulting upper limits are:

resonance	mass-range [MeV]	events in mass-range	$\Gamma(R\to\gamma\gamma)\cdot BR(R\to p\bar{p}\pi^+\pi^-)$ [keV]
$\eta_c(2984)$	2984±44	0	< 0.42 (95% c. l.)
$\chi(3415)$	3415±60	2	< 1.13 (95% c. l.)
$\chi(3555)$	3555±64	2	< 0.37 (95% c. l.)

Since we found no evidence for resonance production, we give in Fig. 3b the cross section for the reaction $\gamma\gamma\to p\bar{p}\pi^+\pi^-$ assuming phase space like production. Also shown is the cross section for $\gamma\gamma\to p\bar{p}$ measured in this experiment /6/ extrapolated to $|\cos\Theta^*|\leqq 1$. In the region of overlap the two cross sections are of comparable magnitude.

In summary, two photon production of the $p\bar{p}\pi^+\pi^-$ final state was observed in the c. m. energy range between 2.5 and 5.0 GeV. The cross section for the reaction $\gamma\gamma\to p\bar{p}\pi^+\pi^-$ was determined assuming phase space production. No evidence was found for the production of $\Lambda\bar{\Lambda}$, $\Delta^{++}\overline{\Delta^{++}}$, $\Delta^\circ\overline{\Delta^\circ}$ or $p\bar{p}\rho^\circ$, and upper limits on the cross sections were determined. Upper limits were also derived on the product of the $\gamma\gamma$-width times the decay branching ratio into $p\bar{p}\pi^+\pi^-$ of the $\eta_c(2984)$, $\chi(3415)$ and $\chi(3555)$.

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FIGURE CAPTIONS

Fig. 1 a) The larger m_{TOF}^2 of the positively charged particles versus the larger m_{TOF}^2 of the negatively charged particles for four prong events with net charge zero ($|\vec{p}| \leq 1.6$ GeV/c, $|\sum \vec{p}_\perp| <$ 0.14 GeV/c).

b) The smaller m_{TOF}^2 of the positively charged particles versus the smaller m_{TOF}^2 of the negatively charged particles for four prong events with net charge zero and with one identified $p\bar{p}$ pair.

c) Distribution of $|\sum \vec{p}_\perp|^2$ of the $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ system. The histogram shows the Monte Carlo prediction for phase space production of $\gamma\gamma \to p\bar{p}\pi^+\pi^-$.

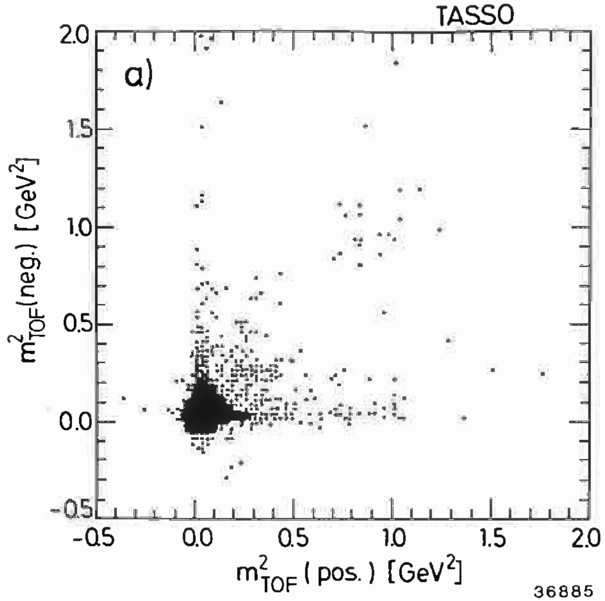
Fig. 2 a) Uncorrected distribution of the c. m. energy of $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ events. Also shown is the energy dependence of the detection efficiency ε for production according to phase space and via $\Lambda\bar{\Lambda}$ pairs (dashed lines).

b) Scatter plot of the invariant mass of the $p\pi^-$-system versus the invariant mass of the $\bar{p}\pi^+$-system for the $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ events.

c) Scatter plot of the invariant mass of the $p\pi^+$-system versus the invariant mass of the $\bar{p}\pi^-$-system for the $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ events.

Fig. 3 a) Upper limits (95% c. l.) on the cross sections for baryon pair production in two photon collisions for $|\cos\Theta^*| \leq 0.6$.

b) Cross sections for the reaction $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ assuming phase space production. Also shown is the cross section for $\gamma\gamma \to p\bar{p}$ from Ref. /6/, extrapolated to $|\cos\Theta^*| \leq 1$.



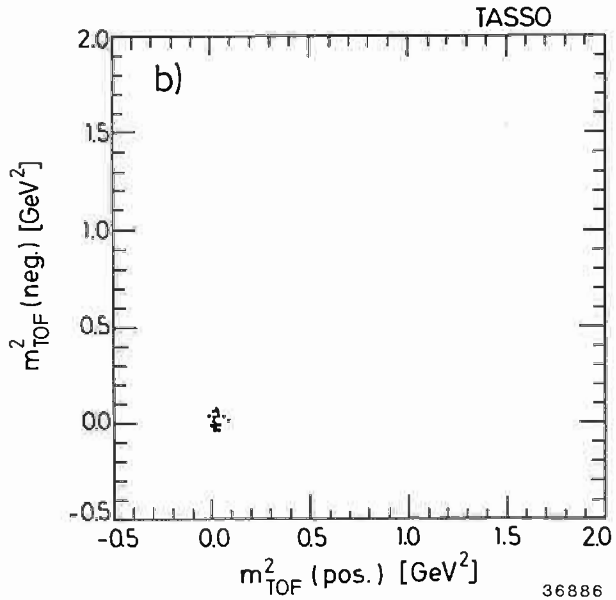


Fig. 1

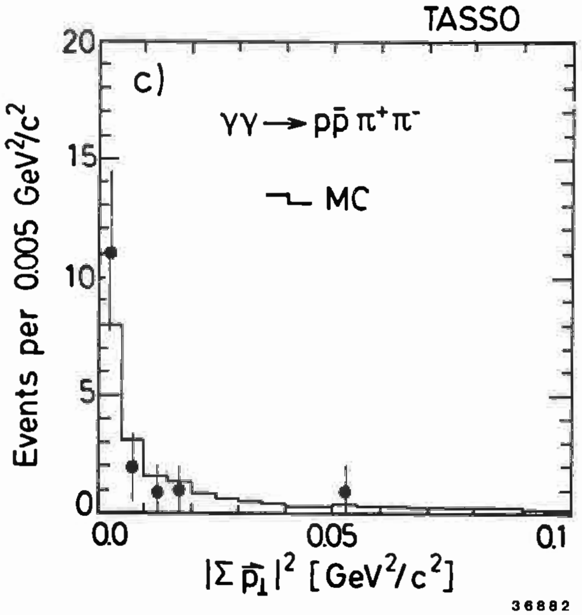


Fig.1

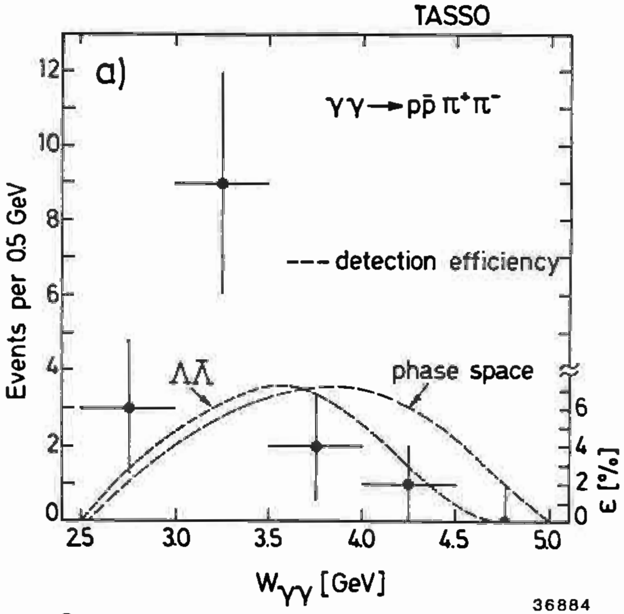
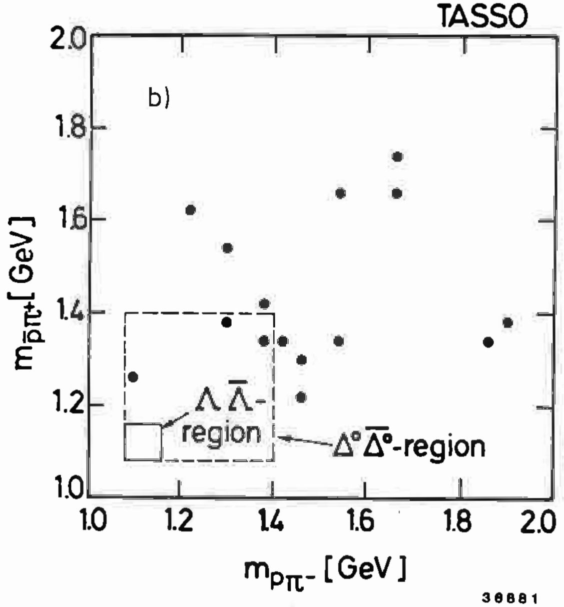


Fig.2



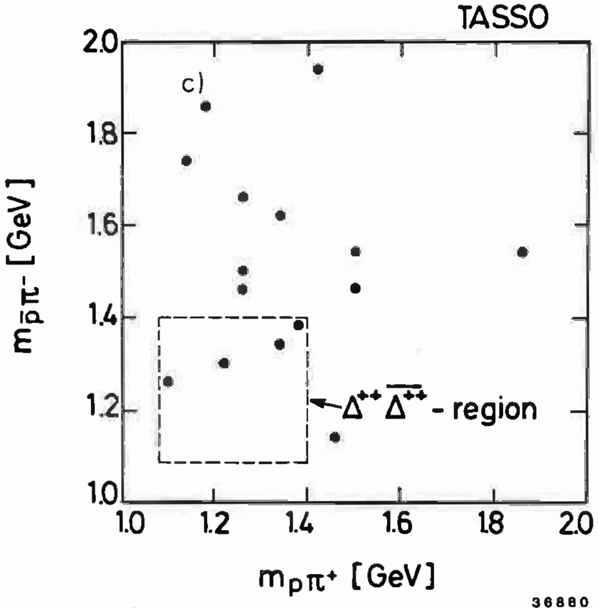
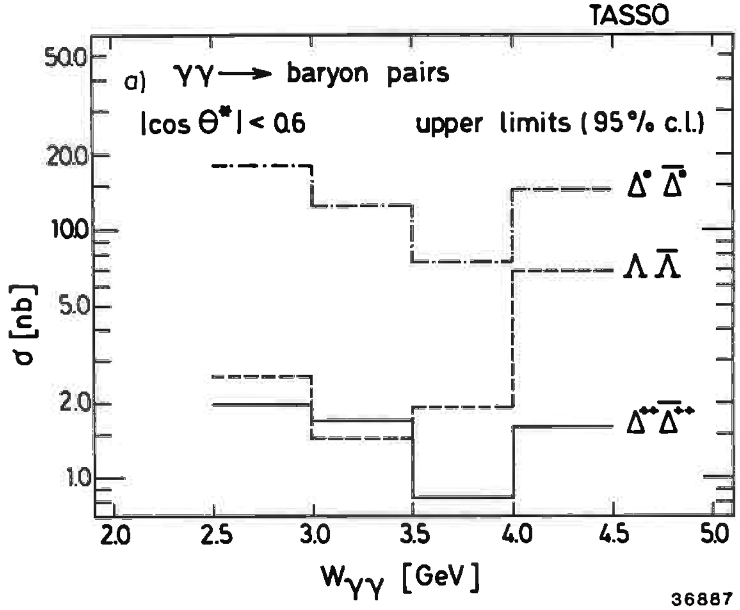


Fig.2


TASSO
a) γγ ⟶ baryon pairs
|cos Θ*| < 0.6
upper limits (95% c.l.)
Δ° Δ̄°
Λ Λ̄
Δ⁺⁺ Δ̄⁺⁺
σ [nb]
W_γγ [GeV]
36887

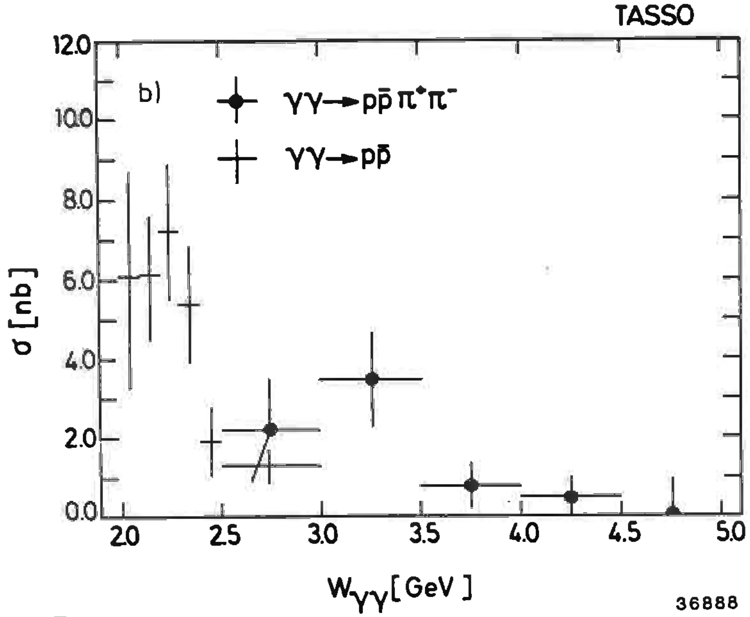

TASSO
b)
γγ ⟶ pp̄ π⁺π⁻
γγ ⟶ pp̄
σ [nb]
W_γγ [GeV]
36888

Fig. 3