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Measurement of the Two-Photon Reaction $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$ at large values of Q^2

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Abstract: The process $\gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-$ has been investigated in reactions of the type $e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^+\pi^-$ in the single tag mode. The range of the four momentum squared of one of the virtual photons was $0.28\ \mathrm{GeV}^2/c^2 \leq Q^2 \leq 3.6\ \mathrm{GeV}^2/c^2$, the average being $\langle Q^2 \rangle = 0.92\ \mathrm{GeV}^2/c^2$; the other photon was quasi real. The reaction is mainly described by the channels $\gamma\gamma \rightarrow \rho^0\rho^0$ and $\gamma\gamma \rightarrow 4\pi$ (phase space), occuring with about equal probability. The Q^2-dependence of the cross section is in agreement with the ρ form factor.

1. Introduction

The relatively large cross section of the two photon reaction $\gamma\gamma \rightarrow \rho^0\rho^0$ near threshold which was measured by the TASSO collaboration [1] and subsequently by other experiments [2], [3], [4], [5] is still not completely understood, despite a number of theoretical attempts [6].

This has been our motivation for studying this reaction further. In our previous experimental work $Q^2 = |q^2|$, the modulus of the invariant momentum transfer squared, was small for both virtual photons. In this work we study this reaction for the case in which one of the two virtual photons has a large value of Q^2, in order to see how the characteristics of the reaction change when one of the two photons is highly virtual.

2. Experimental Procedure and Data Selection

The data were taken with the TASSO detector at the PETRA storage ring at CM energies between 35 GeV and 46.6 GeV. The total integrated luminosity used for this analysis was 150 pb^{-1}, concentrated at about 35 GeV CM energy. The TASSO detector has been described before [7]; here we give a brief description of the components most relevant for this work. More details can be found in [8].

Charged tracks used in this analysis were reconstructed using the cylindrical drift chamber [9] and proportional chamber..

Within polar angles $37° < \theta < 143°$ tracks can be recorded in all 15 layers of the central drift chamber. The track detectors are in solenoidal magnetic field of 0.5 T, leading to a momentum resolution at 90° of

$$\sigma_p/p = 1.7\ \%\ \sqrt{1+p^2} \quad (p \text{ in GeV/c})$$

The track chambers are also used in the trigger. They allow the recognition of tracks above a predetermined value of the transverse momentum $p_t = 220$ MeV/c with respect to the beam direction. The trigger efficiency for one track was measured to be about 80% for $p_t > 220$ MeV/c.

Particles at small forward or backward angles are measured by a pair of tagging counters, one in the forward and one in the backward direction. Each tagging counter consists of a hodoscope counter to provide angle information for the incident particle, followed by a shower counter for energy measurement. The shower counter consists of 40 layers of lead (3 mm) - scintillator (5 mm) - sandwich. The hodoscope counter consists of 6 layers of square proportional tubes, which are arranged in three double layers with an angle of 22.5° between them. The angular resolution achieved is $\sigma_\theta = 1.3 \pm 0.2$ mrad (polar angle), and $\sigma_\phi = 80 \pm 15$ mrad (azimuth angle).

The polar angle range covered by these counters is 30 mrad - 105 mrad with respect to the beam line in the forward and backward directions.

The trigger used to select candidates for two photon reactions required at least one track recognized in the inner central track detector in addition to an energy $E > W/6$ deposited in the forward or backward shower counters, W being the e^+e^- CM energy.

The reaction we want to study is $e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^+\pi^-$. The following selection criteria were used in the off-line analysis to select candidate events:

1) There are exactly four tracks in the inner detector, passing close to the interaction point, resulting from two positively and two negatively charged particles.

2) Their angles θ lie between 37° and 143° with respect to the beam line ($|\cos\theta| < 0.8$).

3) Their transverse momenta with respect to the beam line are larger than 100 MeV/c; at least one track has a transverse momentum $p_t > 280$ MeV/c.

4) There is exactly one hit in the forward or backward shower counters at an angle $30 \text{ mrad} < \theta < 90 \text{ mrad}$ with respect to the beam line.

5) The energy E of the particle producing the hit, as measured in the shower counter, satisfies $E > 0.33\ W$.

Conditions 4) and 5) imply that one of the two virtual photons has a relatively large value of Q^2, $Q^2 > 0.28$ GeV^2/c^2, whereas the other virtual photon will have a very small value of Q^2.

A total of 389 events fulfilled the conditions 1)-5). In order to eliminate events which do not belong to the exclusive reaction $e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^+\pi^-$ because they have additional undetected particles in the final state, and in order to provide a check that the non-tagged photon has a small value of Q^2, the following conditions 6), 7) based on transverse momentum conversation were applied:

6) $$\Delta p_t{}^2 = \Big(\Big|\sum_{i=1}^{4} \vec{p}_{ti}\Big| - |\vec{p}_{ts}|\Big)^2 < 0.035\ \text{GeV}^2/\text{c}^2$$

where $\Sigma\vec{p}_{ti}$ is the vector sum of the momenta of the four charged tracks in the inner detector, projected in the plane perpendicular to the beam line, and $\vec{p}_{ts}$ is the transverse momentum of the particle detected in the forward or backward shower detectors.

7) $168° < |\Delta\phi| < 192°$

where $\Delta\phi$ is the difference of the azimuth angles of $\Sigma\vec{p}_{ti}$ and $\vec{p}_{ts}$.

A total of 100 events remained after conditions 6) and 7). Among these events we identified one as being due to the reaction $\gamma\gamma \rightarrow \pi^+\pi^-K^+K^-$ by time of flight measurements, two events were identified as $\gamma\gamma \rightarrow K^0\pi^+K^-$ or $\gamma\gamma \rightarrow K^0\pi^-K^+$ and six events had a converted photon. These events were removed from the sample leaving 91 events as our candidates for the reaction $\gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-$.

These events were used in the subsequent analysis. They still contained some background:

At momenta above 0.5. GeV/c unique pion-kaon separation by TOF becomes difficult; from our work on the reaction $\gamma\gamma \rightarrow \pi^+\pi^-K^+K^-$ [10] we estimate that there are three events in our sample, which have kaon tracks not recognized by the time of flight measurement because of their large momenta. There is one beam-gas event, estimated from the distribution of event vertices along the beam axis. The background from events which have additional unrecognized particles was determined by leaving off one of the four tracks of our events; after checks 6) and 7) for momentum conservation the estimated background from non-exclusive events is 4.6. The background due to annihilation was negligible (0.2 events), as determined from a study of our annihilation events. This total background of 9% was statistically subtracted.

The data cover a range of $W_{\gamma\gamma}$ (CM energy of the four charged hadrons) 0.6 GeV $< W_{\gamma\gamma} <$ 3.5 GeV, with with a mean of $\langle W_{\gamma\gamma}\rangle = 1.8$ GeV. The Q^2-range was $0.28\ \mathrm{GeV}^2/c^2 < Q^2 < 3.6\ \mathrm{GeV}^2/c^2$, with a mean of $\langle Q^2\rangle = 0.92\ \mathrm{GeV}^2/c^2$. A more detailed account of this work, based on a smaller data sample, is also available [8].

3. Acceptance Calculations

In order to compute the acceptance of the detector, a complete Monte Carlo simulation of events was carried out. Tracks were generated and followed through the detector. The same trigger conditions and the same conditions 1)-7) of the previous section were applied to the Monte Carlo data to calculate the efficiency of detecting events. This efficiency is somewhat dependent on the model used for the production mechanism. We investigated the reaction types: (i) $e^+e^- \to e^+e^-\pi^+\pi^-\pi^+\pi^-$, with the four pions distributed according to phase space (ii) $e^+e^- \to e^+e^-\rho^0\rho^0$, with isotropic production and decay $\rho^0 \to \pi^+\pi^-$; and (iii) $e^+e^- \to e^+e^-\rho^0\pi^+\pi^-$. The cross sections were parametrized in the same way as in our earlier work [1]. Figure 1 shows the efficiency for accepting these three event types, as a function of $W_{\gamma\gamma}$.

4. Results

Figure 2a shows the density plot of one invariant $\pi^+\pi^-$ mass combination versus the other one. There are two entries for each event. Fig. 2b shows the $\pi^+\pi^+$ vs. $\pi^-\pi^-$ mass distribution. Figs. 3a and 3b show for comparison the corresponding plots of the Monte Carlo events mentioned in Section 3) for the 4π phase space and the $\rho^0\rho^0$ event types, respectively.

In order to determine the fractions of observed events of the three reaction types (i)-(iii) in the experimental data, we fitted the two dimensional experimental distributions $m(\pi^+\pi^-)$ vs. $m(\pi^+\pi^-)$ and $m(\pi^+\pi^+)$ vs. $m(\pi^-\pi^-)$ simultaneously to the corresponding two dimensional Monte Carlo distributions. For the Monte Carlo distribution we chose a combination of the three reaction types (i)-(iii), with the fractions as the parameters to be fitted. A maximum likelihood fit was performed in four $W_{\gamma\gamma}$ intervals in the $W_{\gamma\gamma}$-range 1.2 GeV $< W_{\gamma\gamma} <$ 2 GeV and yielded the following relative rates, averaged over the four $W_{\gamma\gamma}$ bins:

(i) $\gamma\gamma \to 4\pi$ (phase space)	43 ± 16%
(ii) $\gamma\gamma \to \rho^0\rho^0$	48 ± 16%
(iii) $\gamma\gamma \to \rho^0\pi^+\pi^-$	9 ± 28%

The contribution of event type (iii) is consistent with being small, but the error is large. In order to investigate the stability of the fit with respect to the fraction of reaction (iii), we repeated it with reactions (i) and (ii) only. We also found an acceptable fit in this case, and the result is

$\gamma\gamma \to 4\pi$ (phase space)	48 ± 13%
$\gamma\gamma \to \rho^0\rho^0$	52 ± 13%

The fractions can be compared with our previous work with almost real photons [1]. Averaging over the same $W_{\gamma\gamma}$ – interval (1.2-2 GeV) we find an average of 60% for the $\rho^0\rho^0$ fraction, compatible with the present work within the errors.

The total cross section for the reaction $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$ as a function of the energy $W_{\gamma\gamma}$ in the four pion CM system is shown in Fig. 4. It is averaged over the range of $0.28\ \mathrm{GeV}^2/c^2 < Q^2 < 3.6\ \mathrm{GeV}^2/c^2$ considered in this paper, and is not sensitive to the errors of the fractions (i)-(iii), as is evident from Fig. 1. There is an estimated 25% overall normalization error (not shown), because the small absolute value of the efficiency implies a large extrapolation with subsequent sensitivity to the details of the Monte Carlo Calculations.

In order to investigate the Q^2-dependence of the cross section we compare it with the result for almost real photons ($Q^2 \approx 0$) Fig. 5 shows the cross section at $Q^2 \approx 0$ as a function of $W_{\gamma\gamma}$, deduced from our previous work [1].

We have averaged this cross section at $Q^2 \approx 0$ from $W_{\gamma\gamma} = 1.2$ GeV to $W = 2$ GeV and compared it with the cross section for large values for Q^2 as obtained in this paper, using the ρ form factor $F_\rho(Q^2) = 1/(1+Q^2/M_\rho^2)$ to describe the Q^2-dependence. This is shown in Fig. 6; the ρ form factor gives a reasonably good description.

Similar results have also been obtained by the TPC/Two Gamma [4] and PLUTO collaborations [5].

5. Conclusion

We have investigated the reaction $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$ for a range of the four momentum squared of one of the virtual photons $0.28\ \mathrm{GeV}^2/c^2 < Q^2 < 3.6\ \mathrm{GeV}^2/c^2$, the average being $<Q^2> = 0.92\ \mathrm{GeV}^2/c^2$. For CM energies in the $\gamma\gamma$ system $W_{\gamma\gamma}$ in the range $1.2\ \mathrm{GeV} < W_{\gamma\gamma} < 2$ GeV the Q^2-dependence of the cross section is in agreement with the ρ form factor. The data require a substantial contribution from the channel $\gamma\gamma \to \rho^0\rho^0$, similar to our earlier findings at $Q^2 \approx 0$. Since a large part of the $W_{\gamma\gamma}$ range in this work is below nominal $\rho^0\rho^0$ threshold, our results indicate that the phenomenon of a large $\gamma\gamma \to \rho^0\rho^0$ cross section near threshold may persist at Q^2 values a round $1\ \mathrm{GeV}^2/c^2$.

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Figure Captions

Fig. 1 Total acceptance as a function of the $\gamma\gamma$ CM energy $W_{\gamma\gamma}$, generated according to the production mechanism $\gamma\gamma \to \rho^0\rho^0$ (dotted line), $\gamma\gamma \to \rho^0\pi^+\pi^-$ (dashed line), $\gamma\gamma \to 4\pi$ (phase space) (solid line)

Fig. 2 Invariant masses $m(\pi^+\pi^-)$ vs. $m(\pi^+\pi^-)$, two entries/event, and $m(\pi^+\pi^+)$ vs. $m(\pi^{--})$ or $m(\pi^-\pi^-)$ vs. $m(\pi^{++})$; the distributions are folded over, with the larger one of the two mass values plotted along the abscissa.

Fig. 3 Invariant masses $m(\pi^+\pi^-)$ vs. $m(\pi^+\pi^-)$, for Monte Carlo events, generated according to a) $\gamma\gamma \to 4\pi$ (phasespace), b) $\gamma\gamma \to \rho^0\rho^0$
The distribution are folded as in Fig. 2.

Fig. 4 The cross section of the reaction $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$ as a function of $\gamma\gamma$ CM energy $W_{\gamma\gamma}$.. Statistical errors only are shown.
The data are averaged over the range of $0.28\ \mathrm{GeV}^2/c^2 < Q^2 < 3.6\ \mathrm{GeV}^2/c^2$ with $\langle Q^2\rangle = 0.92\ \mathrm{GeV}^2/c^2$.

Fig. 5 The cross section $\sigma(\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-)$, for almost real photons ($Q^2 \approx 0$), as a function of $\gamma\gamma$ CM energy $W_{\gamma\gamma}$ as deduced from [1] (see [8]). Also shown are the data of other collaborations [2]-[5].
The errors of Ref. [1] are statistical only.

Fig. 6 The cross section $\sigma(\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-)$, as a function of Q^2, averaged over $1.2\ \mathrm{GeV} < W_{\gamma\gamma} < 2\mathrm{GeV}$, and compared with the point at $Q^2 \approx 0$, deduced from Ref. [1].

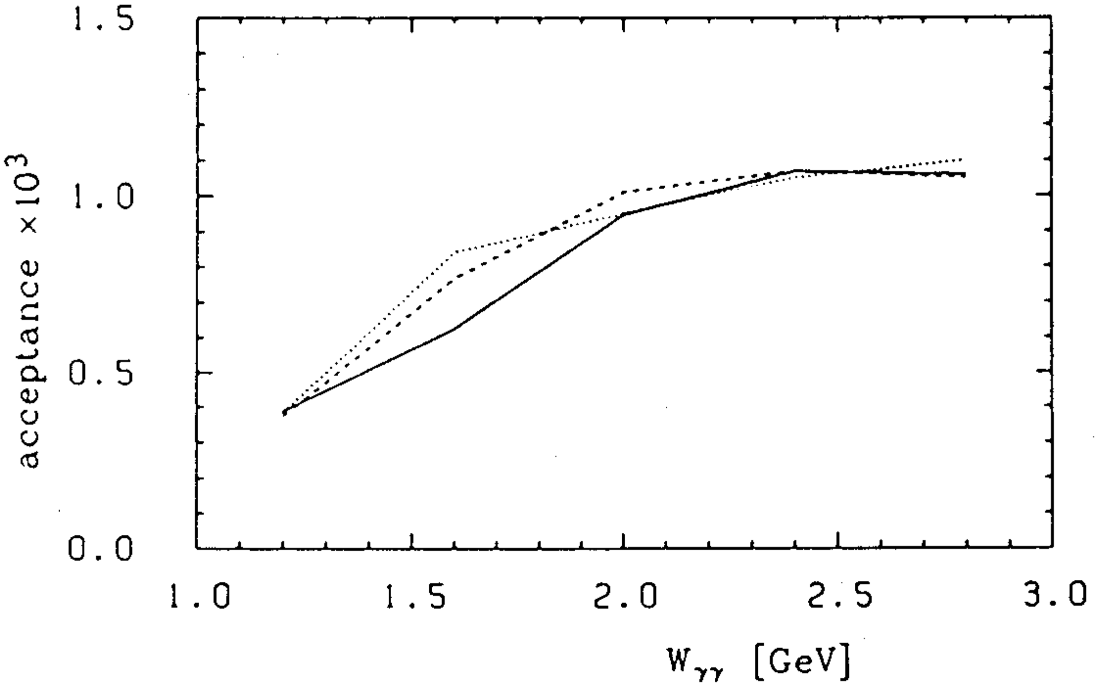

1.5
1.0
0.5
0.0
acceptance ×10^3
1.0
1.5
2.0
2.5
3.0
$W_{\gamma\gamma}$ [GeV]

Fig. 1

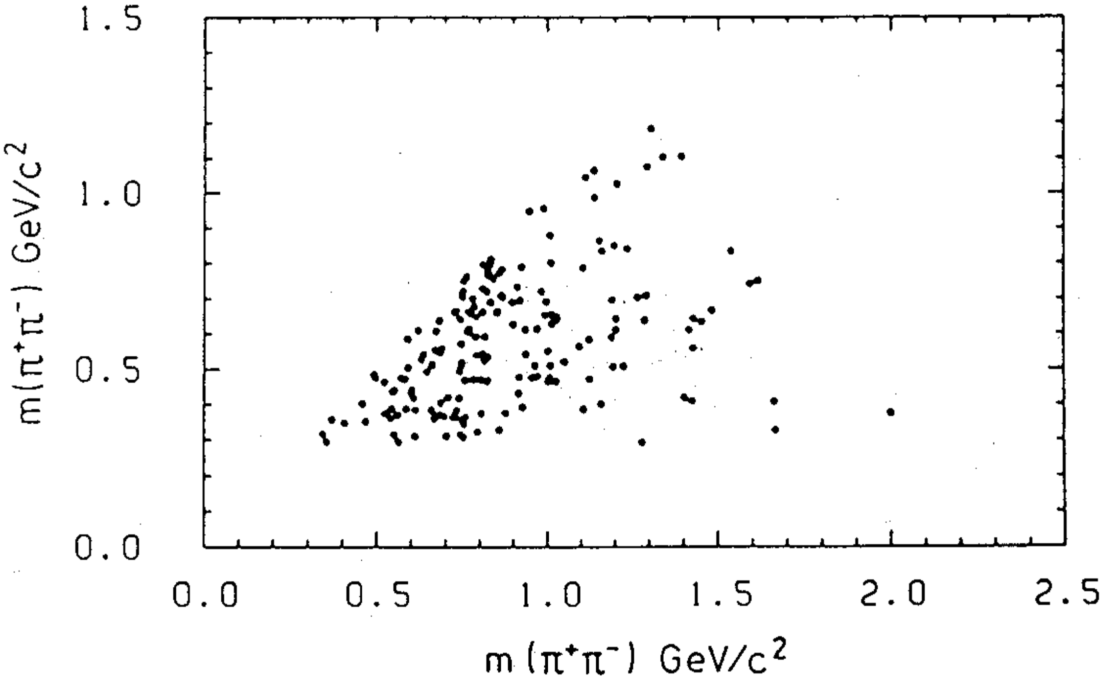

1.5
1.0
0.5
0.0
m($\pi^+\pi^-$) GeV/c^2
0.0
0.5
1.0
1.5
2.0
2.5
m($\pi^+\pi^-$) GeV/c^2

Fig. 2a

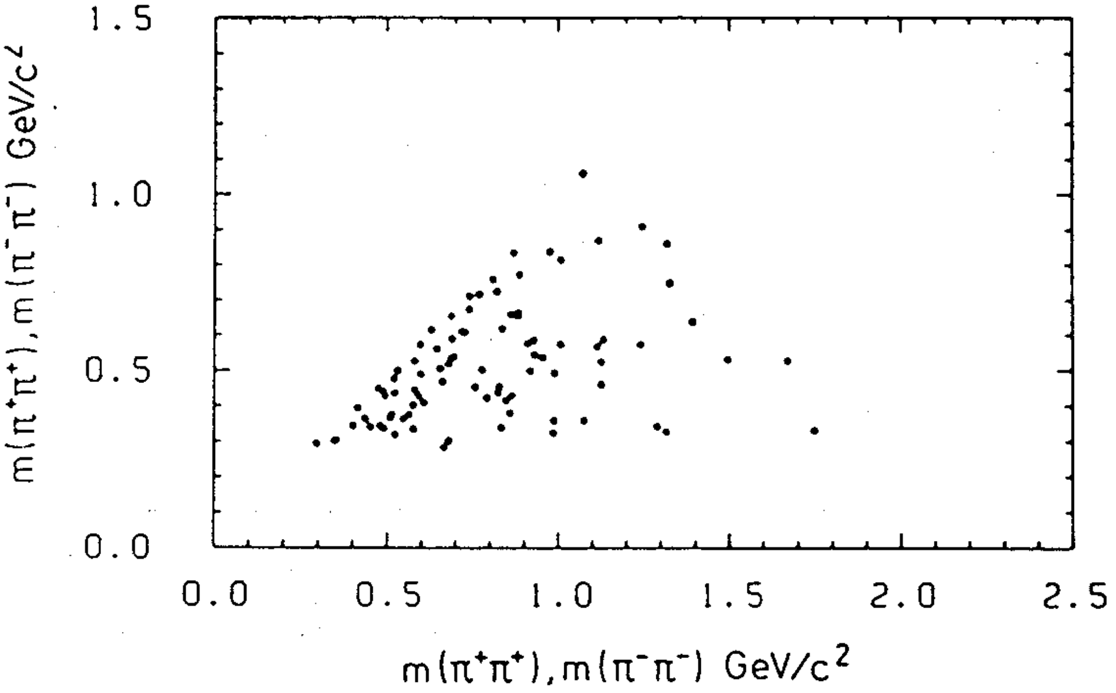
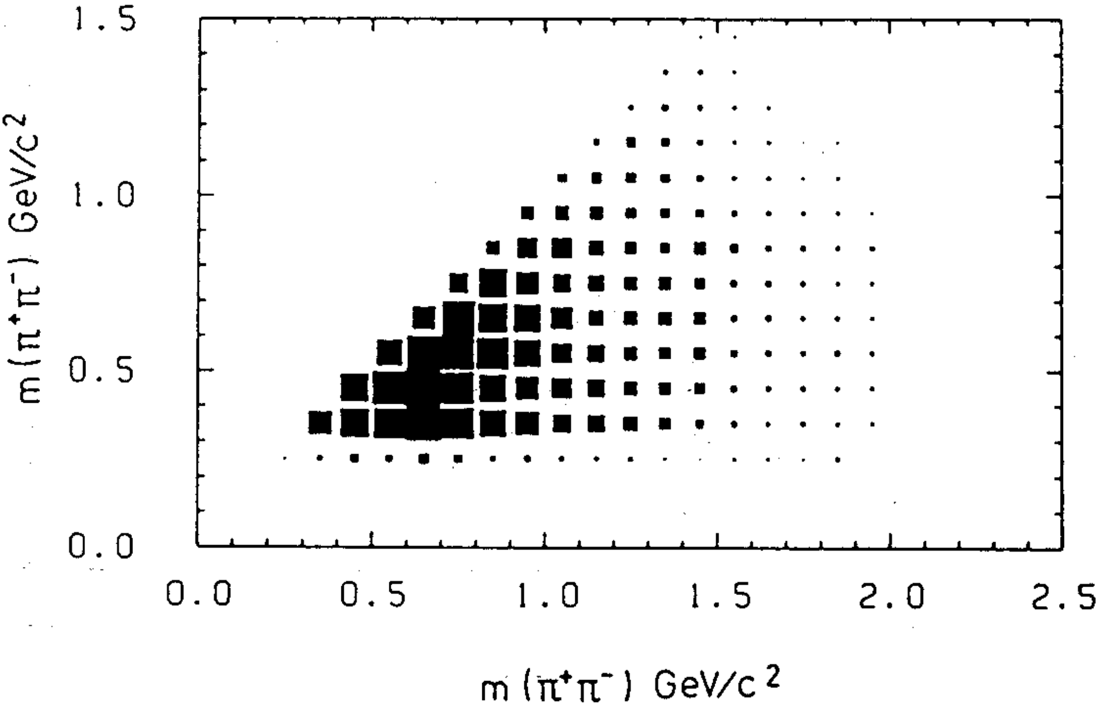

1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
m(π⁺π⁺), m(π⁻π⁻) GeV/c²
m(π⁺π⁺), m(π⁻π⁻) GeV/c²

Fig. 2b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1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
m(π⁺π⁻) GeV/c²
m(π⁺π⁻) GeV/c²

Fig. 3a

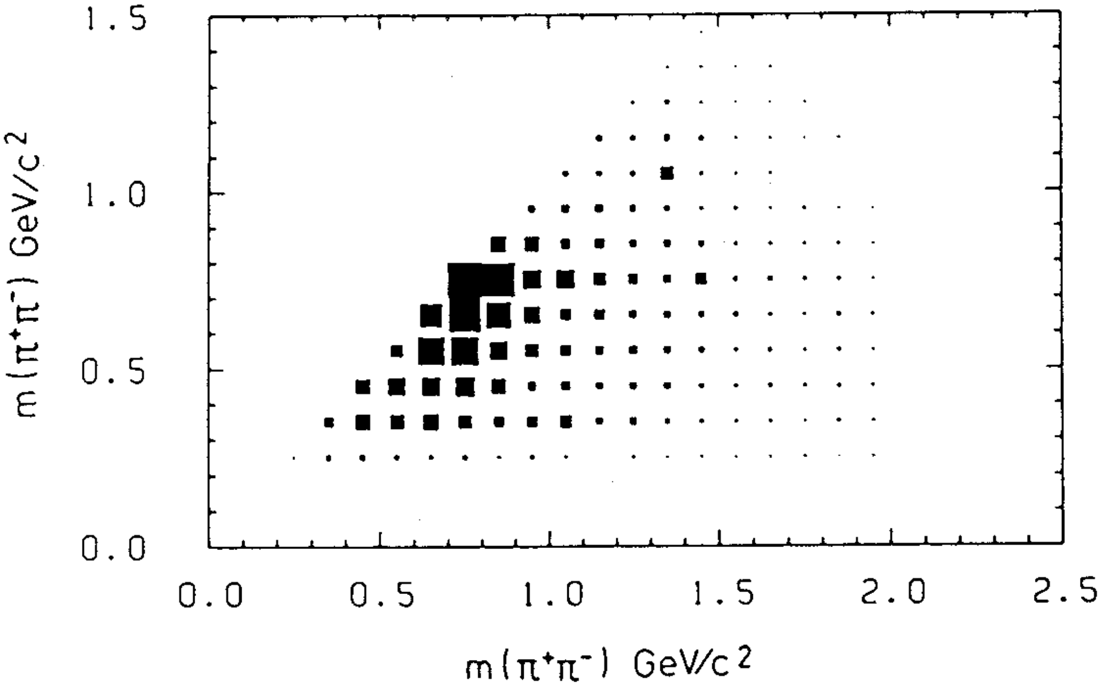

1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
$m(\pi^+\pi^-)$ GeV/c^2
$m(\pi^+\pi^-)$ GeV/c^2

Fig. 3b

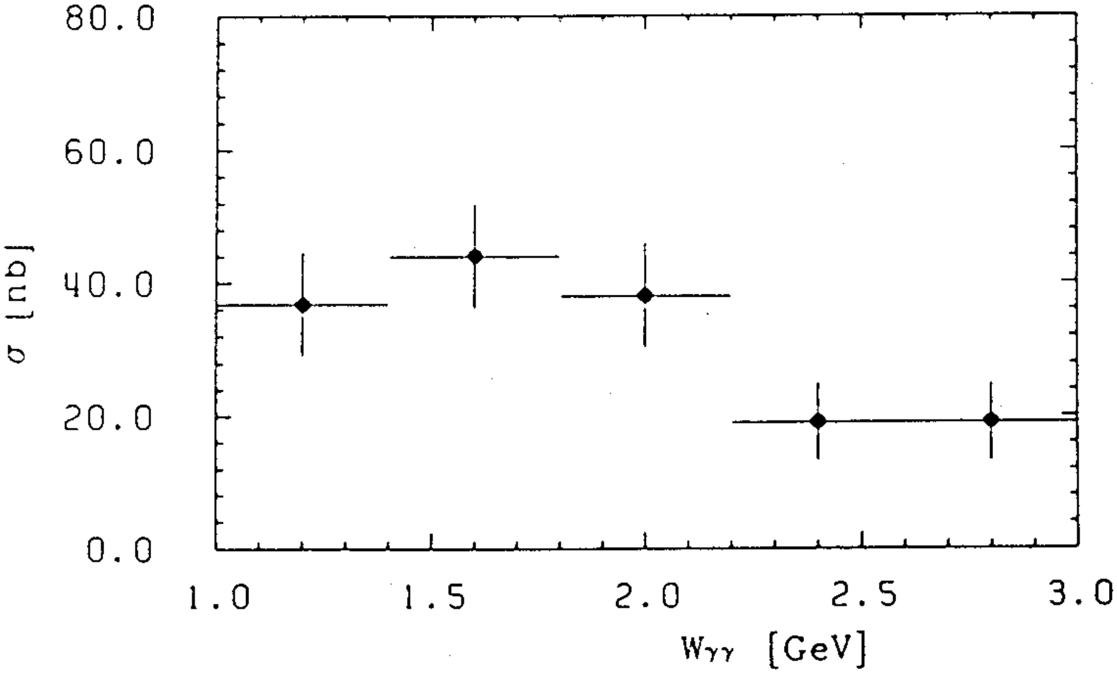
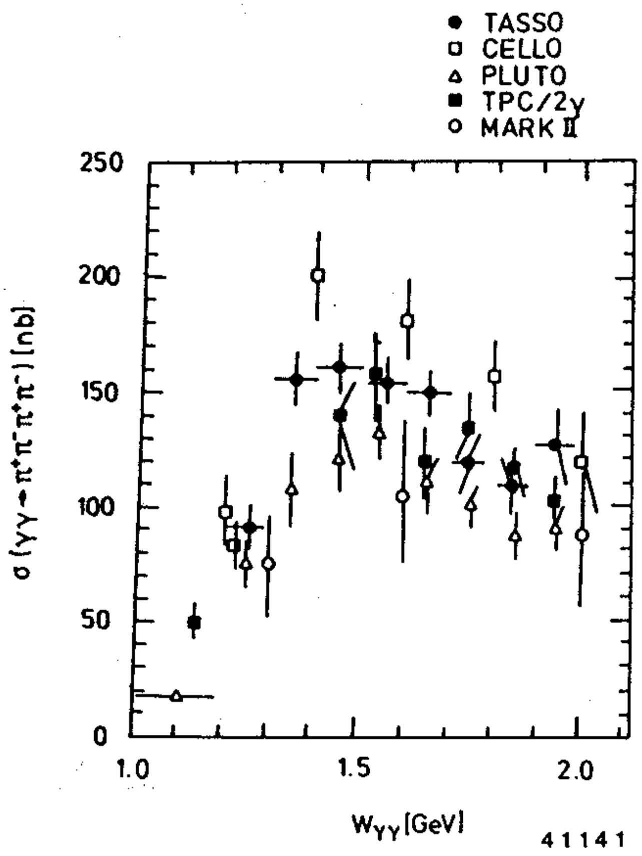

80.0
60.0
40.0
20.0
0.0
σ [nb]
1.0
1.5
2.0
2.5
3.0
$W_{\gamma\gamma}$ [GeV]

Fig. 4


● TASSO
□ CELLO
△ PLUTO
■ TPC/2γ
○ MARK II
σ (γγ → π⁺π⁻π⁺π⁻) [nb]
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200
150
100
50
0
1.0
1.5
2.0
W_γγ [GeV]
41141

Fig. 5

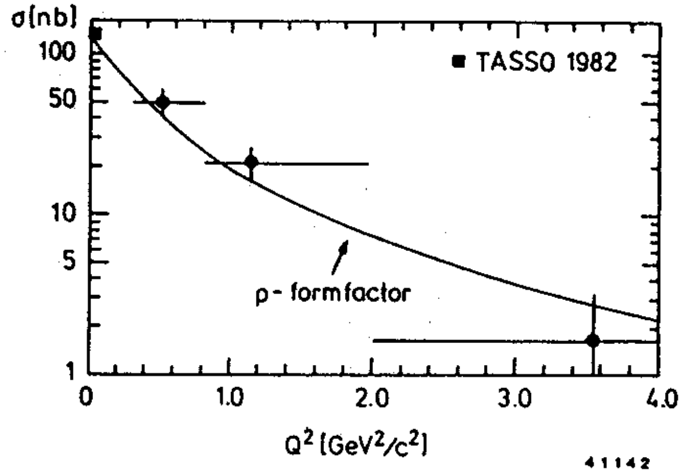
σ [nb]
100
50
10
5
1
■ TASSO 1982
ρ - formfactor
0
1.0
2.0
3.0
4.0
Q² [GeV²/c²]
41142

Fig. 6