Title
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Author
Ronan, M.T.

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IN TWO PHOTON REACTIONS

M.T. Ronan

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Michael T. Ronan
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
U.S.A.

ABSTRACT

Recent experimental results on exclusive final states produced in photon-photon interactions are reviewed. Comparisons between experiments and with perturbative QCD calculations are made for meson and baryon pair production. New results on vector meson pair $(\rho^0\rho^0, \rho^0\omega, \rho^0\phi, \ldots)$ production and production of multiparticle $(KK\pi\pi, K^*K\pi, \ldots)$ final states are summarized.

Presented at the VIIth International Workshop on Photon-Photon Collisions, Collège de France, Paris, April 1-5, 1986.

1. INTRODUCTION

Recent measurements of exclusive final states in two photon reactions will be presented. Production of resonances and measurement of their $\gamma\gamma$ widths are the subject of another review.[1] A brief summary of some of the theoretical predictions which have been compared to the data will be given, while the review of recent theoretical calculations appears elsewhere in these proceedings.[2]

In this report, the production of charged pseudoscalar meson pairs ($\pi^+\pi^-$, K^+K^-) at high mass and baryon pair production are compared to perturbative QCD calculations. New measurements of low mass charged pion production are summarized. Several explanations of the observed $\rho^0\rho^0$ cross section are compared to new measurements of various related channels including vector mesons. The production of multipion channels as well as multiparticle final states including kaons are also discussed. Finally, vector meson $(\rho^0\rho^0, \rho^+\rho^-, \rho^0\omega)$ production is compared to perturbative QCD calculations.

2. MESON PAIR PRODUCTION

2.1 Meson Pair Production in Perturbative QCD

Large angle two photon exclusive processes at high energies can be described by elementary hard scattering followed by soft confinement.[3] Furthermore, counting rule arguments predict[4] that the amplitude is dominated by intermediate states with a minimal number of elementary constituents; thus, for meson pair production, Fig. 1a, we would expect the diagram of Fig. 1b to dominate at high energies.

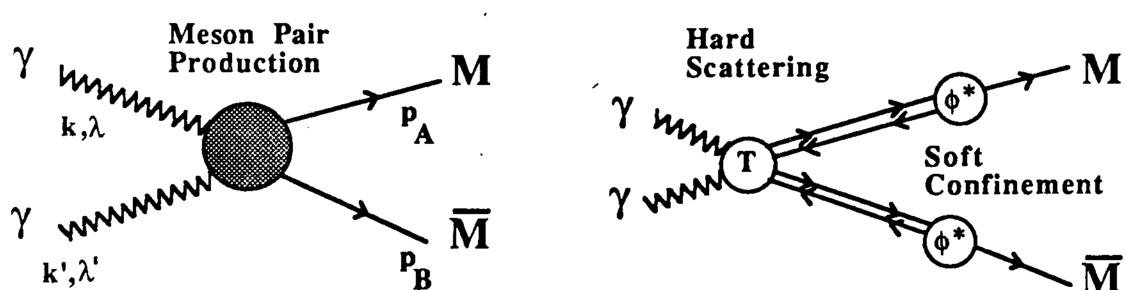


Fig. 1a   Fig. 1b

Fig. 1

Meson pair production in two photon reactions and diagramatic representation of the separation of hard scattering and soft confinement processes.

The helicity amplitude for the reaction is given by

$$M_{\lambda\lambda'}(s,\theta^*) = \int_0^1 dx dy \; \phi_A^*(x,\tilde{Q}_x)\, \phi_B^*(y_1\tilde{Q}_y)\, T_{\lambda\lambda'}(x,y,s,\theta^*) \qquad (1)$$

where $T_{\lambda\lambda'}$ is the transition matrix element for the hard scattering process, ϕ^* is the confinement amplitude and x,y are the momentum fractions of the constituents in the final state hadrons. The confinement amplitude is the complex conjugate of the composite particle's distribution amplitude to be in a state with only two valence quarks with $k_\perp < Q$, $\phi(x,\tilde{Q}_x) = \langle q\bar{q}; k_\perp < Q \mid Meson\rangle$, where Q is the typical momentum transfer in the reaction (Q $\sim$ hadron $p_\perp$) as illustrated in Fig. 2.

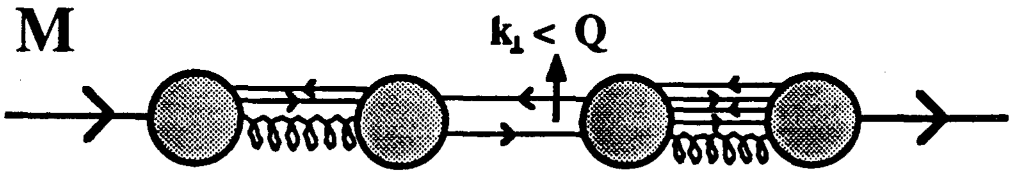
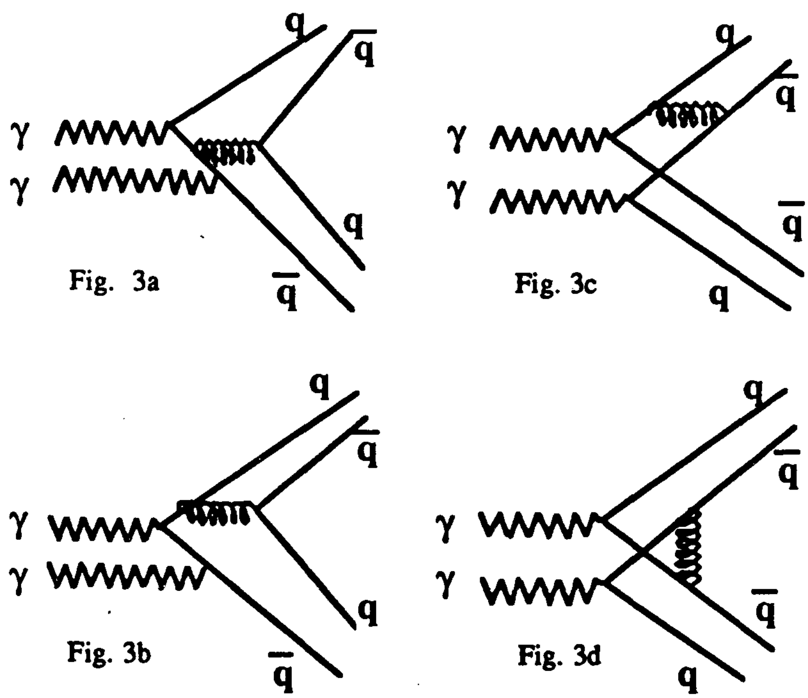


Fig. 2
Illustration of various states for a composite meson including the nearly collinear two quark state.

The transition matrix element for meson pair production has been calculated in perturbative QCD to lowest order in α_s. There are a total of forty (40) diagrams in all with the four (4) independent diagrams shown in Fig. 3.

Fig. 3
Independent hard scattering diagrams for meson pair production in lowest order QCD.



The non-perturbative confinement amplitude has not been calculated. However, Brodsky and Lepage have noticed[3)] that the x dependence of the hard scattering matrix element is similar to that appearing in the meson's electromagnetic form factor which also includes these same confinement amplitudes. One is then able to express the cross section for meson pair production in terms of the measured form factor and a correction term which has been estimated for several functional forms of the meson's distribution amplitude. Figure 4 displays the invariant cross section for pion pair production for three forms of this distribution amplitude. The prediction for $\pi^+\pi^-$ production is quite insensitive to the correction term and has an expected angular distribution of

$$\frac{d\sigma}{dt} \sim \frac{1}{(1-\cos^2\theta^*)^2} \tag{2}$$

where θ^* is the CM scattering angle.

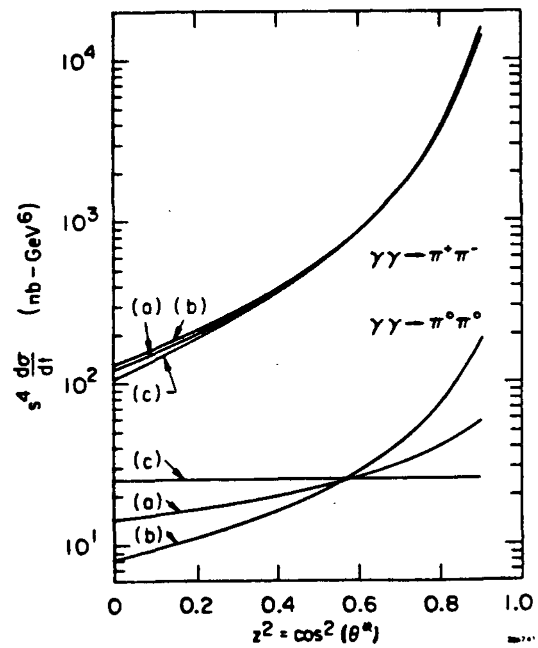


Fig. 4
Invariant cross section prediction[3)] for pion pair production for the following forms of the pion distribution amplitude. $\phi(x,\tilde{Q})$: a) $x(1-x)$, b) $[x(1-x)]^{1/4}$, c) $\delta(x-1/2)$.

Since the normalization of the distribution amplitude for different mesons can be determined from the meson's decay constant

$$f_m = 2\sqrt{3}\int_0^1 dx \;\; \phi_m(x,Q), \tag{3}$$

one can use the decay constants from K, ρ, ω and ϕ leptonic decay to predict the relative yield of these meson pairs compared to pion pair production assuming the x dependence of the distribution amplitudes are similar. Thus, for kaon pair production we would expect

$$\frac{d\sigma}{dt}(\gamma\gamma \to K^+K^-)/\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-) \simeq \frac{|f_k|^4}{|f_\pi|^4} \simeq 2 \qquad (4)$$

where decay constants $f_\pi = 93$ MeV and $f_K = 112$ MeV have been used.[5] Differences in the hard scattering diagrams of Figs. 3a-b and in the kaon distribution amplitude will modify this prediction.

2.2 Measurements of Pseudoscalar Meson Pair Production

At the last Two Photon Workshop held at Lake Tahoe in 1984, the PLUTO collaboration presented a measurement of low mass $\pi^+\pi^-$ production using their forward spectrometers. Their data showed a possible enhancement near threshold and a dip near 650 MeV/c^2 when compared to the Born calculation. The TPC/Two Gamma collaboration at PEP has now also measured[6] low-mass pion pair production using dE/dx particle identification to separate the large e^+e^- background and to statistically separate and measure the $\mu^+\mu^-$ background. Their result, shown in Fig. 5, does not confirm the dip observed by the PLUTO collaboration at $M_{\gamma\gamma} \simeq 650$ MeV/c^2 and is in reasonable agreement with the Born approximation down to 500 MeV/c^2. However, their data do not extend down to the threshold region of 300-400 MeV/c^2.

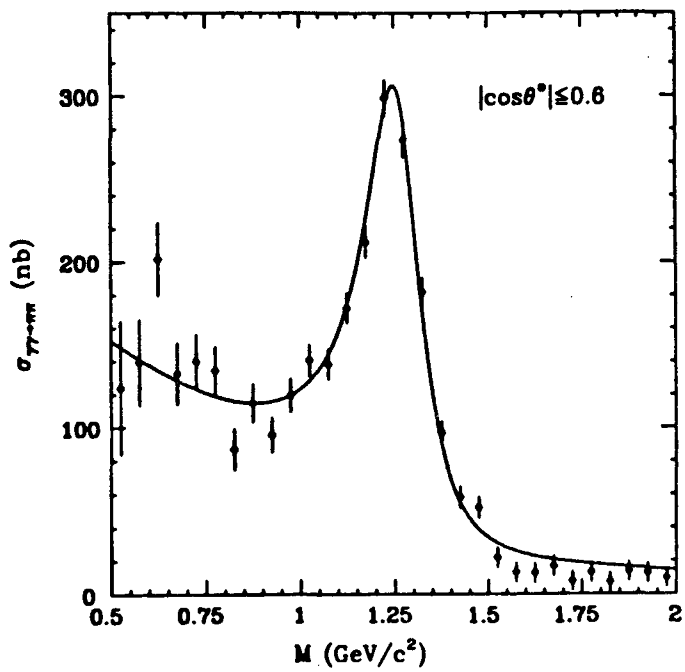


Fig. 5
Low mass $\pi^+\pi^-$ production for $|\cos\theta^*| \leq 0.6$, where θ^* is the CM scattering angle, from the TPC/Two Gamma collaboration. The curve is a fit of a f^0 resonance interfering with a Born-term continuum.

New measurements of low mass $\pi^+\pi^-$ production extending down to $\pi\pi$ threshold have been obtained by the DCI group at Orsay. Their data seem to show[7)] a low mass enhancement below 500 Mev/c^2.

The MARK II collaboration has recently published[8)] their results on high mass charged pion and kaon production, based on 230 inverse picobarns of data, and their comparison to perturbative QCD predictions. In their measurement, e^+e^- and $\mu^+\mu^-$ backgrounds are separated using the calorimetry and muon detectors of the MARK II, respectively. Without the aid of particle identification pions and kaons are not separated. Their data are binned in $M_{\pi\pi}$ and $\cos\theta^*$ where the prediction of Brodsky and Lepage is used to determine the weighting of π and K efficiencies in each bin. Their data for two different $\cos\theta^*$ bins are shown versus $M_{\pi\pi}$ in Fig. 6. There appears to be good agreement for $M_{\pi\pi} > 2.1$ GeV/c^2 in the large angle region, Fig. 6a, and reasonable agreement within the limited statistics of Fig. 6b for $M_{\pi\pi} > 1.7$ GeV/c^2 in the small angle region $0.3 <|\cos\theta^*| < 0.5$.

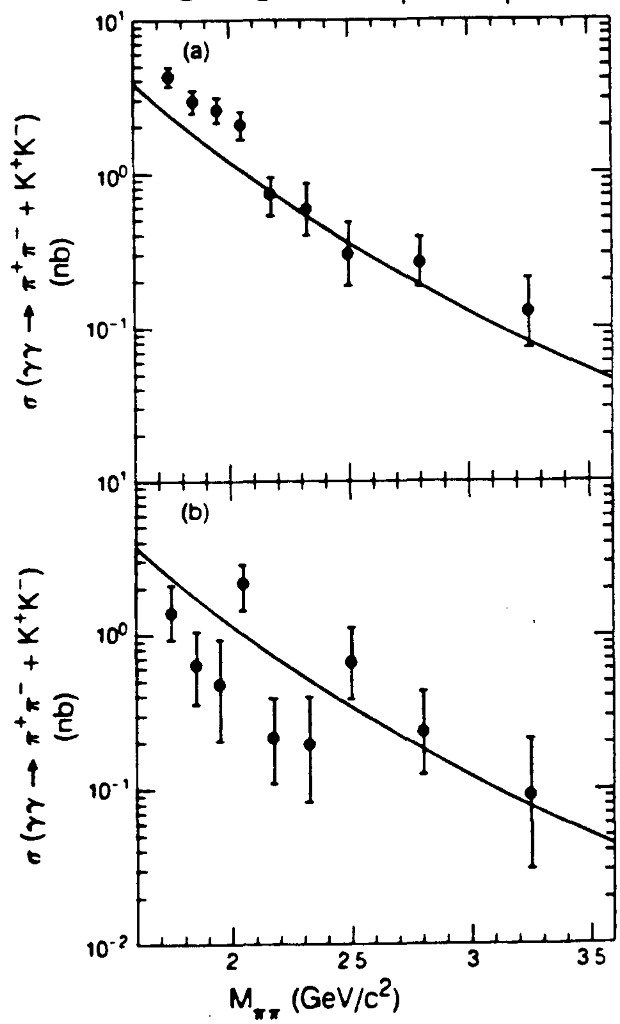


Fig. 6
High mass $\pi^+\pi^-$ plus K^+K^- production from the MARK II collaboration for
(a) $|\cos\theta^*| \leq 0.3$
(b) $0.3 <|\cos\theta^*| \leq 0.5$.
The curves are absolute predictions of Ref. 3.

The angular acceptance of the MARK II detector with muon identification is limited to $|\cos\theta^*| < 0.5$. The angular distribution of the $\pi^+\pi^-$ plus K^+K^- cross section for the mass region $2.1 < M_{\pi\pi} < 3.5$ GeV/c^2 is in reasonable agreement with the perturbative QCD predictions[3], Fig. 7; however, the statistics are quite limited and the data are clearly also consistent with a flat $\cos\theta^*$ distribution.

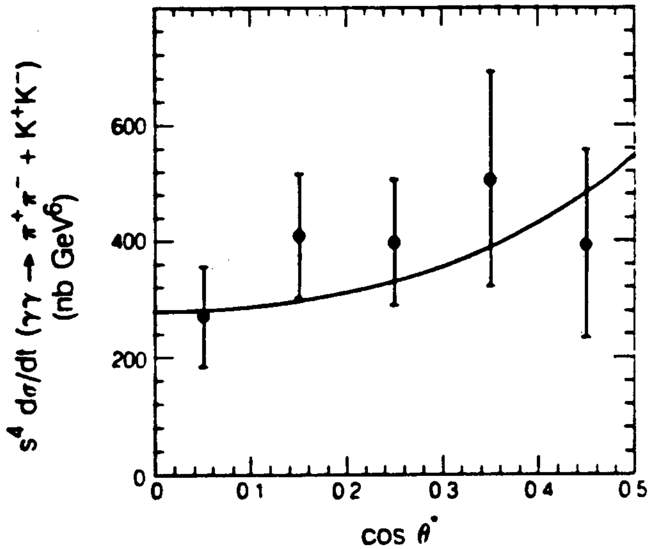


Fig. 7
Angular distribution of $\pi^+\pi^-$ plus K^+K^- production from the MARK II collaboration.

The MARK II group has also presented an uncorrected Q^2 distribution for their data, shown in Fig. 8. The data show excellent agreement between their Monte Carlo calculation of the expected $\mu^+\mu^-$ rate and their $\mu^+\mu^-$ measurement. The fall off of the $\pi^+\pi^-$ plus K^+K^- yield with Q^2 is much faster than the hard $\mu^+\mu^-$ yield but since no high mass cut was applied the measurement is dominated by low mass resonance production.

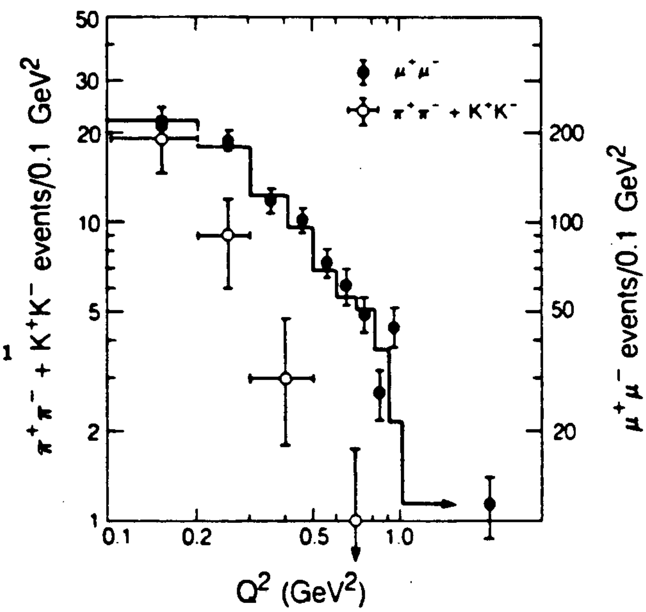


Fig. 8
Q^2 distribution of the $\mu^+\mu^-$ and $\pi^+\pi^-$ plus K^+K^- yields in the MARK II detector for their 230pb^{-1} sample.

At this workshop, the TPC/Two Gamma collaboration has presented[9] final results on $\pi^+\pi^-$, K^+K^- production based on their $75pb^{-1}$ sample. In this experiment, pions and kaons are separated by measurement of dE/dx in the Time Projection Chamber. Electrons are separated by dE/dx as well, while muons are identified using the central muon detectors. The data have limited statistics compared to the MARK II measurement because of the lower integrated luminosity and since the data are divided into $\pi^+\pi^-$ and K^+K^- samples. The data are shown in Fig. 9. For the mass region, $1.5 < M_{\gamma\gamma} < 2.5$ GeV/c^2, the comparison to perturbative QCD predictions indicates that the $\pi^+\pi^-$ cross section is approaching the prediction from a factor of two above and the K^+K^- cross section is somewhat lower than present perturbative QCD calculations. Resonances in the $\pi^+\pi^-$ and K^+K^- channels as well as nonperturbative effects at these low masses will alter these simple theoretical predictions.

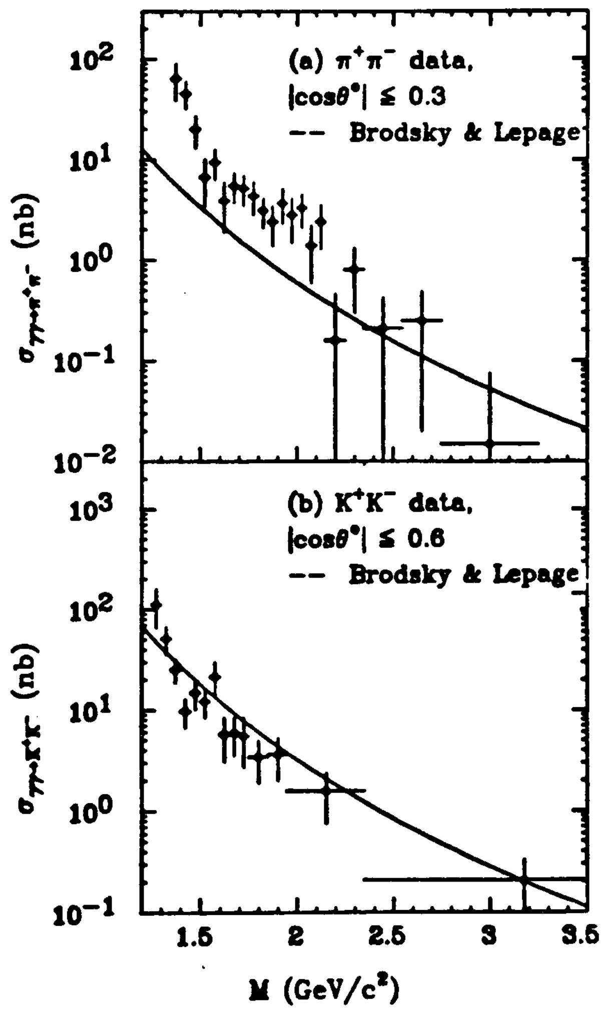


Fig. 9
Cross sections for $\pi^+\pi^-$ and K^+K^- production from the TPC/Two Gamma collaboration.

3. BARYON PAIR PRODUCTION

3.1 Baryon Pair Production in Perturbative QCD

At high energies and large angles, the production of baryon pairs is expected to proceed through hard scattering diagrams of the type shown in Fig. 10.

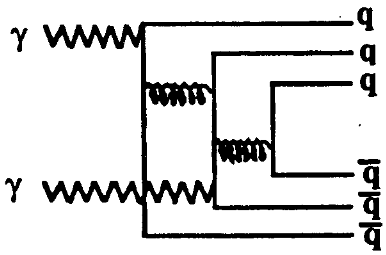


Fig. 10a

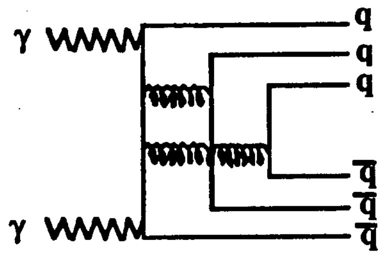


Fig. 10b

Fig. 10
Hard scattering diagrams for baryon pair production in lowest order QCD.

The perturbative QCD calculation of these diagrams was discussed at the last Two Photon Workshop by Glenys Farrar.[10)] The distribution amplitudes which describe the confinement of the quark triplets into baryons are only predicted asymptotically by QCD. For the Q^2 range presently accessible, various wave functions including those derived from QCD sum rules[11)] have been tried. However, the estimates based on these wave functions disagree by an order of magnitude and at the low masses presently accessible to experiments the predictions for $p\bar{p}$ production are at least an order of magnitude below the data.

The calculation of the relative yield of various baryon pairs may be more reliable. Farrar has reported[10)] the predictions for various pairs shown in Fig. 11. Roughly, one obtains

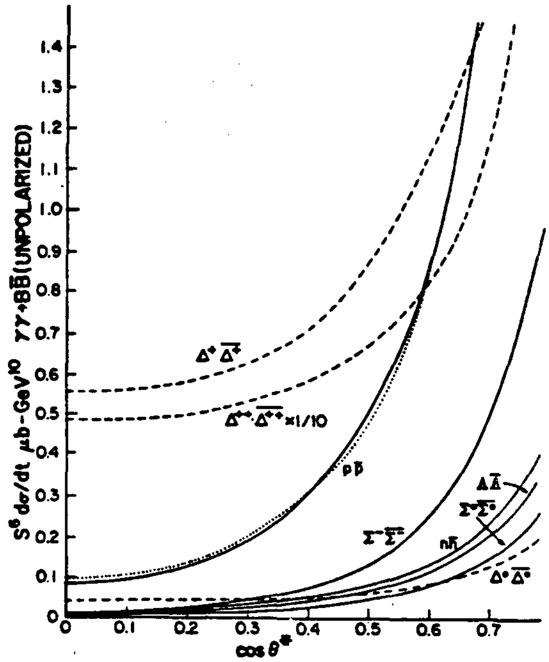
$$\frac{d\sigma}{dt}(\gamma\gamma \to \Delta^+\overline{\Delta^+})/\frac{d\sigma}{dt}(\gamma\gamma \to p\bar{p}) \sim 3-6 \qquad (5)$$

and

$$\frac{d\sigma}{dt}(\gamma\gamma \to \Delta^{++}\overline{\Delta^{++}})/\frac{d\sigma}{dt}(\gamma\gamma \to p\bar{p}) \sim 50 \qquad (6)$$

It is easy to check the expected relative yield of equal spin pairs such as $\Delta^{++}\overline{\Delta^{++}}/\Delta^+\overline{\Delta^+}$ using particle interchanges and the charges of the constituent quarks. Since measurements of $p\bar{p}$ production in two photon reactions have been made, one would hope to measure $\Delta^+\overline{\Delta^+}$ and $\Delta^{++}\overline{\Delta^{++}}$ pair production and compare with these predictions.

Fig. 11
Predictions for baryon pair production in two photon reactions.



3.2 Measurements of Baryon Production

New results on $p\bar{p}$ production from the JADE[12)] and TPC/Two Gamma[13)] groups have been presented at this conference. The JADE results are final, while the TPC/Two Gamma results are preliminary. The measured cross sections for $|\cos\theta^*| < 0.6$ are compared to the published[14)] TASSO results in Fig. 12.

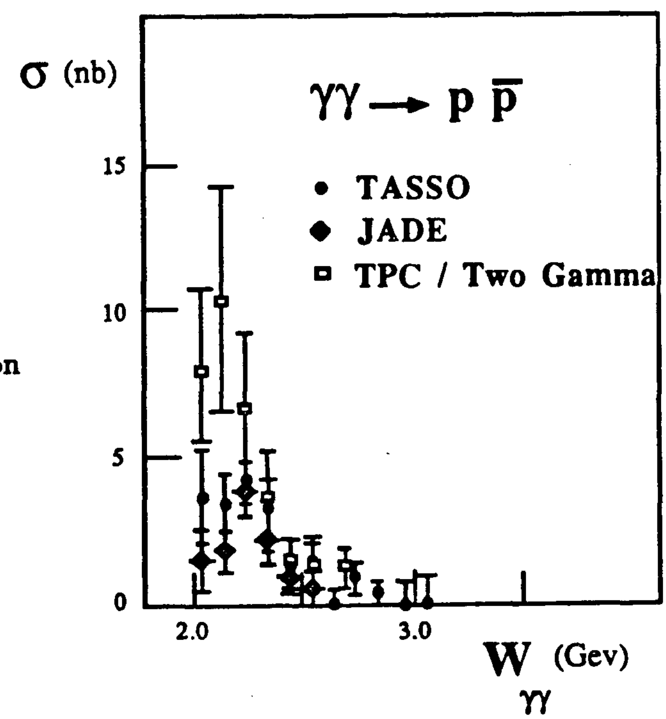


Fig. 12
Proton-antiproton production in two photon collisions.

One observes that there is good agreement between the experiments for $W_{\gamma\gamma} > 2.2$ GeV/c^2. At lower mass, detector effects are quite large and there appears to be some disagreement in the measurements.

Both the TASSO[15] and TPC/Two Gamma[16] groups have measured $p\bar{p}\pi^+\pi^-$ production. These measurements are sensitive to $\Delta^0\overline{\Delta^0}$, $\Lambda\bar{\Lambda}$ and $\Delta^{++}\overline{\Delta^{++}}$ production. Both experiments find the data are consistent with phase space distributions and that there is no significant production of baryon-antibaryon pairs. The exclusive cross section measurements for $p\bar{p}\pi^+\pi^-$ production are compared in Fig. 13a. One finds good agreement except for the lowest mass point where again detector effects are large. The $p\bar{p}$ cross section measured by the TPC/Two Gamma collaboration has been corrected assuming an isotropic distribution and is compared to the $p\bar{p}\pi^+\pi^-$ cross section in Fig. 13b. One notices that the $p\bar{p}\pi^+\pi^-$ cross section is about an order of magnitude larger than the $p\bar{p}$ cross section at $W_{\gamma\gamma} \simeq 2.5$ GeV and that the threshold production cross sections are approximately equal.

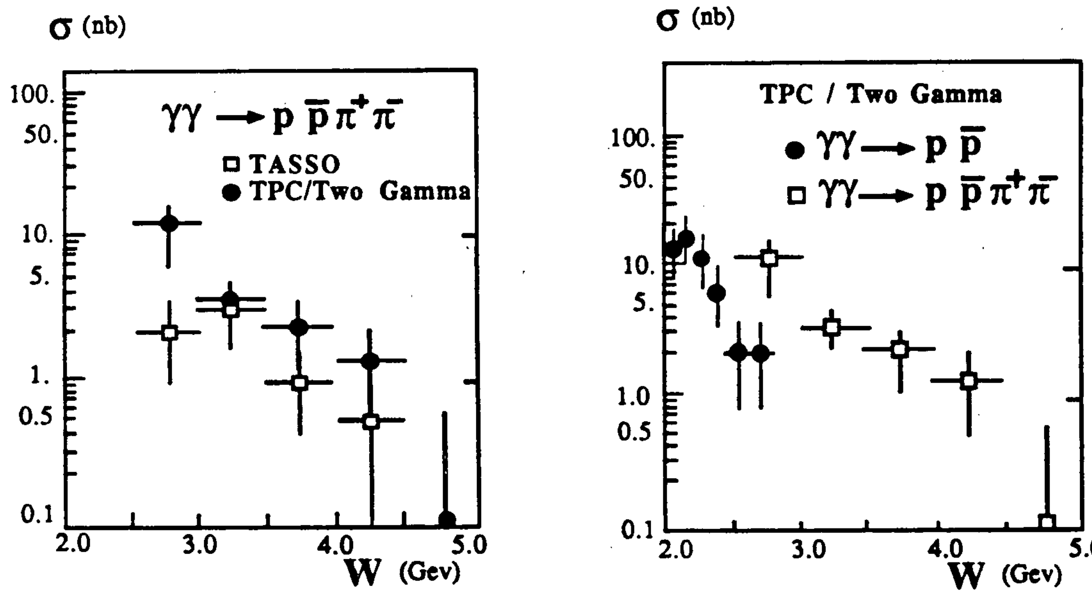


Fig. 13a $\gamma\gamma$

Fig. 13b $\gamma\gamma$

Fig. 13

Cross section for $p\bar{p}\pi^+\pi^-$ production and comparison to $p\bar{p}$ production.

The TASSO collaboration has given[15] upper limits for $\Delta^0\overline{\Delta^0}$, $\Lambda\bar{\Lambda}$ and $\Delta^{++}\overline{\Delta^{++}}$ production. These upper limits and the TPC/Two Gamma measurement of the $p\bar{p}$ cross section are compared to perturbative QCD predictions in Fig. 14.

In the figure, the upper and lower estimates of the $p\bar{p}$ cross section[10] are used to draw a band indicating the level of uncertainty in the $p\bar{p}$ estimates. For other baryon pairs, the estimates[10] and an order of magnitude increase in these estimates form the uncertainty bands of Fig. 14.

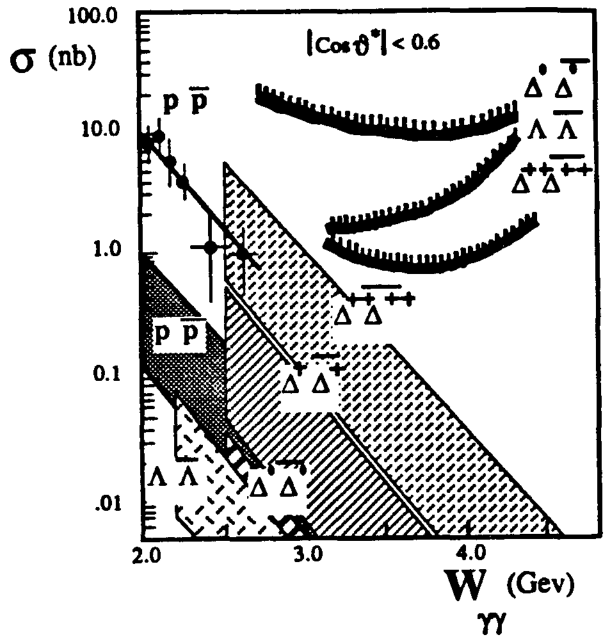


Fig. 14
Comparison of baryon pair production to perturbative QCD predictions. The curve through the data points indicates the predicted W dependence, W^{-10}, with arbitrary normalization.

The JADE collaboration has also presented a measurement of the angular distribution of $p\bar{p}$ production shown in Fig. 15. The data are compared to the perturbative QCD estimate using the Chernyak-Zitnitsky wave function.[10),11)] There is obviously no agreement in this mass range, $2.0 < W_{\gamma\gamma} < 2.6$ GeV/c^2. Clearly, one needs to extend the measurements of baryon pair production to higher masses to compare to these perturbative calculations. In addition, a better understanding of baryon wave functions is necessary.[2)]

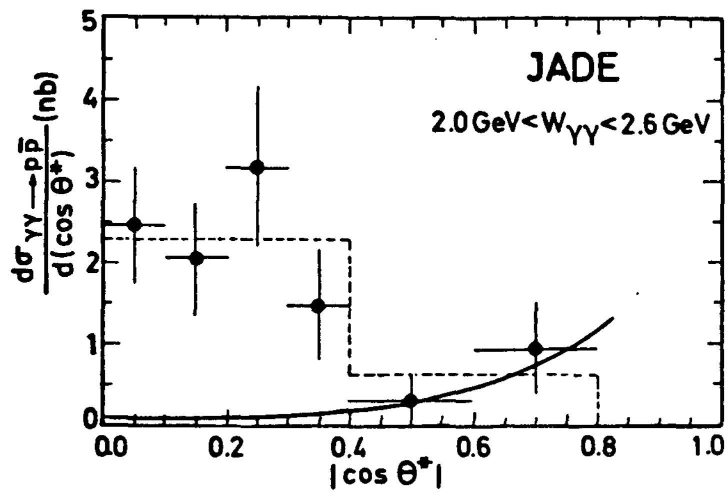


Fig. 15
Angular distribution of $p\bar{p}$ production from the JADE collaboration.

4. MULTIPION PRODUCTION

In this section the production of exclusive multipion final states will be discussed, while vector meson pair production will be addressed in the next section. Several groups have measured the producton of three, four and five pion exclusive final states in two photon reactions. New results on $\pi^+\pi^-\pi^0$ production have been submitted to this conference by the TASSO collaboration.[17] Their measurement is shown in Fig. 16.

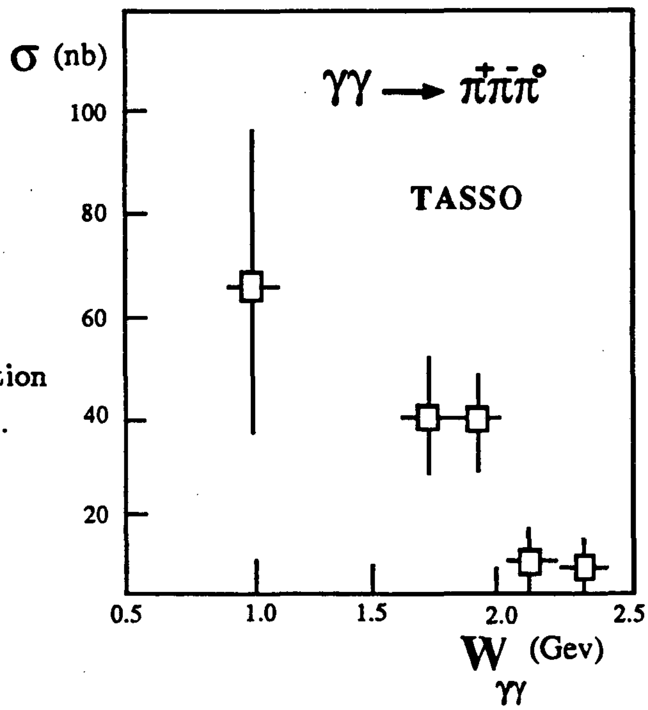


Fig. 16
Cross section for $\pi^+\pi^-\pi^0$ production from the TASSO collaboration.

The production of four pion states at low invariant mass is dominated by $\rho^0\rho^0$ production but the fraction of $\rho^0\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ increases at higher masses. In Fig. 17 cross section measurements for these latter final states have been abstracted from the TPC/Two Gamma measurements of four pion production.[18] The smooth curves drawn through the data points in Fig. 17 should be noted for comparison to other final states which will be made in the next section.

Final results from the PLUTO collaboration[19] on $\pi^+\pi^-\pi^+\pi^-\pi^0$ are shown in Fig. 18. The measured multipion cross sections tend to be approximately 20 to 50 nb at low mass, $W_{\gamma\gamma} \sim 1-1.5$ GeV/c^2, and to decrease with increasing invariant mass. The production of events with kaons or with some evidence for resonances within the multiparticle system are discussed in the next section.

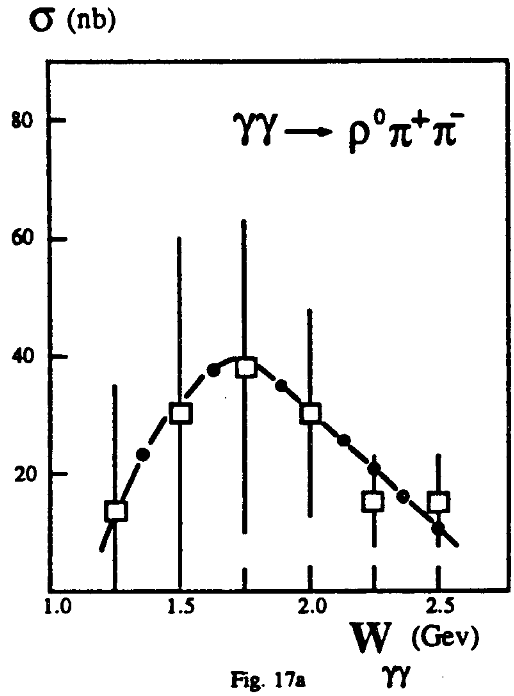


Fig. 17a

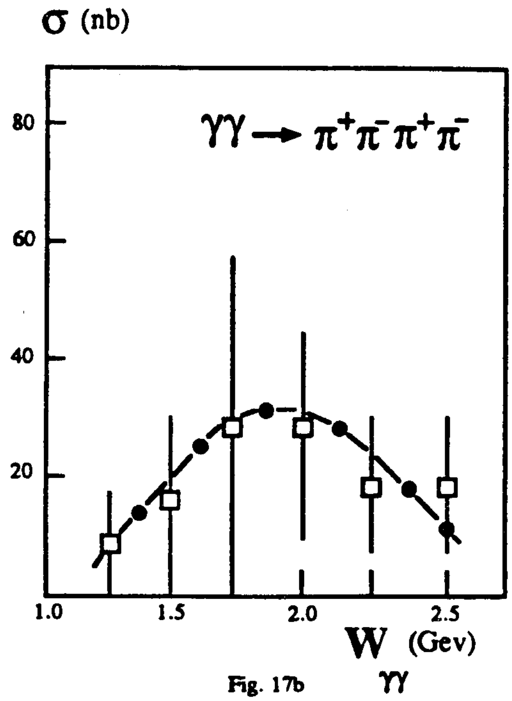


Fig. 17b

Fig. 17
Cross sections for $\rho^0\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ production from the TPC/Two Gamma collaboration.

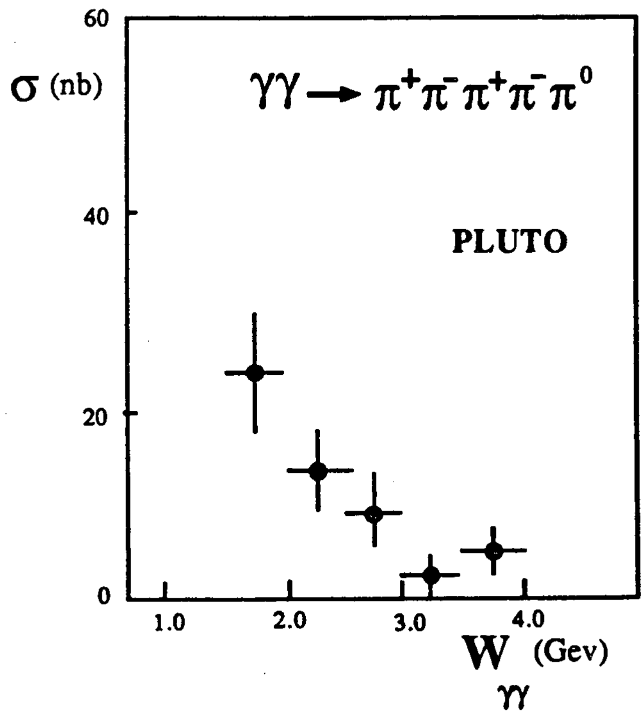


Fig. 18
Cross section for $\pi^+\pi^-\pi^+\pi^-\pi^0$ from the PLUTO collaboration.

5. MEASUREMENTS OF VECTOR MESON PRODUCTION

5.1 Vector Meson Pair Production

Observation of copious $\rho^0\rho^0$ production, initially made by the TASSO collaboration[20], has been confirmed by several groups such as CELLO[21] and TPC/Two Gamma[18]. The resulting cross section measurements are shown in Fig. 19. The smooth curve shown in Fig. 19 is a hand fit to the data which will be used to compare to other final states.

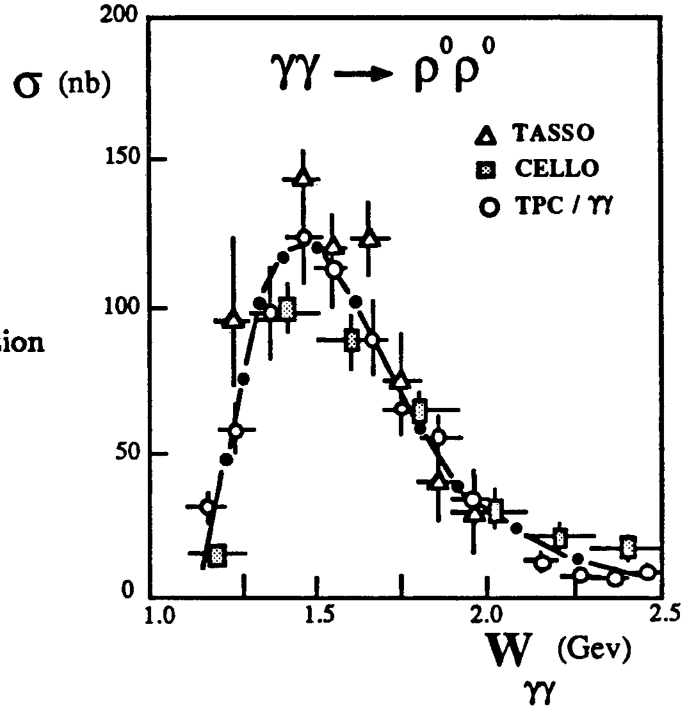


Fig. 19
Cross section for $\rho^0\rho^0$ production in two photon reactions.

These measurements have been discussed in several reviews.[22),23] Possible explanations include: 1) a coupling of the initial state photons to ρ^0 mesons and a large elastic $\rho^0\rho^0$ scattering cross section, 2) a sum of diffractive and t-channel processes,[24] 3) a single $q\bar{q}$ or $qq\bar{q}\bar{q}$ resonance and 4) interfering $qq\bar{q}\bar{q}$ resonances.

The first possibility does not actually explain the resulting $\rho^0\rho^0$ scattering cross section. However, if one assumes Vector Meson Dominance[25] and that the low energy vector meson scattering cross sections for ρ^0, ω and ϕ are similar, then one can predict other cross sections using the standard photon-vector meson couplings[26]

$$\left|\rho^0\right\rangle = \frac{1}{\sqrt{2}}(\left|uu\right\rangle - \left|d\bar{d}\right\rangle) \quad \left|\omega\right\rangle = \frac{1}{\sqrt{2}}(\left|u\bar{u}\right\rangle + \left|d\bar{d}\right\rangle) \quad \left|\phi\right\rangle = \left|s\bar{s}\right\rangle \tag{7}$$

$$\left\langle\rho^0 \mid \gamma\right\rangle \propto \frac{1}{\sqrt{2}}(\frac{2}{3}e - (\frac{-1}{3}e)) \quad \left\langle\omega \mid \gamma\right\rangle \propto \frac{1}{\sqrt{2}}(\frac{2}{3}e + (\frac{-1}{3}e)) \quad \left\langle\phi \mid \gamma\right\rangle \propto \frac{-1}{3}e$$

as indicated in Fig. 20.

Fig. 20
Photon vector meson couplings.

Thus, using the expected photon-vector meson coupling of $\rho : \omega : \phi = 1 : \frac{1}{3} : \frac{\sqrt{2}}{3}$, one might expect

$$\sigma^{peak}_{\rho\omega} \sim \frac{1}{9}\sigma^{peak}_{\rho^0\rho^0} \simeq 13nb \qquad \sigma^{peak}_{\omega\omega} \sim (\frac{1}{9})^2\sigma^{peak}_{\rho^0\rho^0} \simeq 1.5nb \tag{8}$$

$$\sigma^{peak}_{\rho\phi} \sim \frac{2}{9}\sigma^{peak}_{\rho^0\rho^0} \simeq 26nb$$

Figure 21 shows the published upper limits on $\rho^0\omega$ and $\omega\omega$ production from the JADE[27)] and PLUTO[19)] groups. One can see that the simple prediction above had not been excluded prior to this conference. New results on $\omega\pi^+\pi^-$ and $\omega\rho^0$ production will be discussed in the last part of this section.

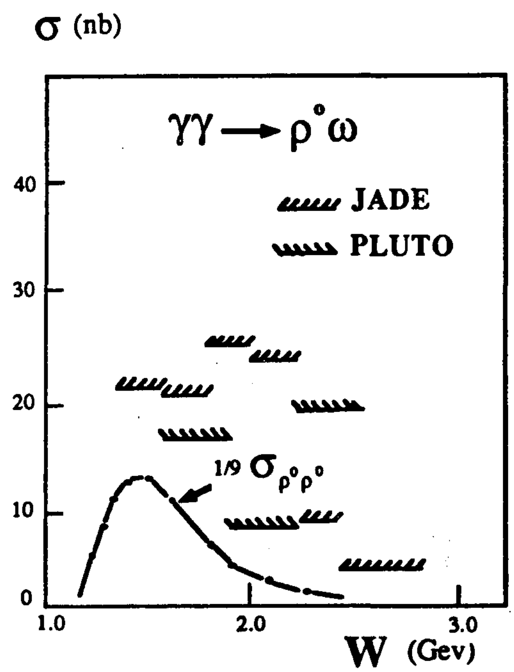


Fig. 21a

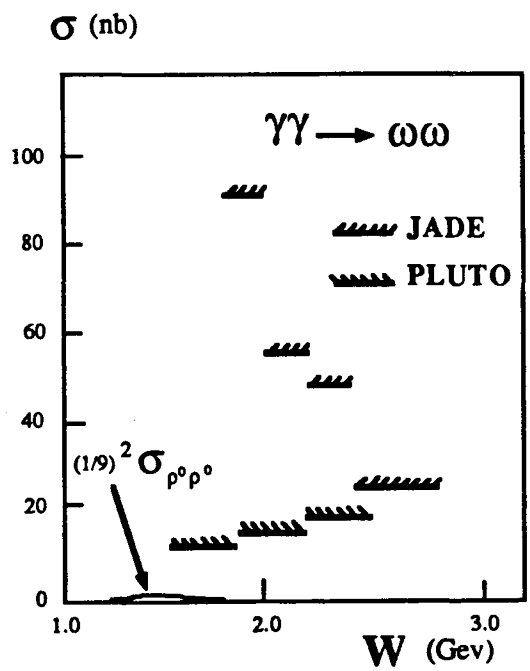


Fig. 21b

Fig. 21
Upper limits for $\rho^0\omega$ and $\omega\omega$ production.

Attempts have been made to explain the observed cross section by including t-channel processes in addition to the diffrative process. In considering t-channel processes such as π^0 and η exchange one is quite sensitive to the large $\omega - \pi^0 - \gamma$ coupling, shown in Fig. 22, measured in radiative decay, $\Gamma(\omega \rightarrow \pi^0\gamma) \sim 861$ keV[5] ($\Gamma(\rho^0 \rightarrow \pi^0\gamma) \sim 67$ keV for comparison).

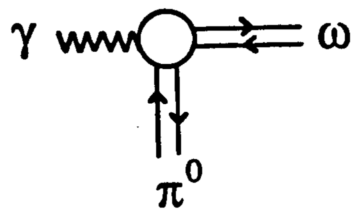


Fig. 22
Diagram indicating ω - π^0 - γ coupling.

Initial explanations of the $\rho^0\rho^0$ cross section using diffractive and t-channel processes predicted large $\omega\omega$ production which have been ruled out by the measurements shown in Fig. 21b. An updated version of this calculation[24] is in agreement with the experimental measurements.

An explanation of the $\rho^0\rho^0$ enhancement as a single $q\bar{q}$ or $qq\bar{q}\bar{q}$ resonance has been ruled out by a measurement of $\rho^+\rho^-$ production. For an isospin 0 or 2 resonance (isospin 1 is not allowed), the cross section for $\rho^+\rho^-$ production would be 2 or 1/2 the $\rho^0\rho^0$ cross section for $I = 0$ *or* 2, respectively. Figure 23 displays a measurement of $\pi^+\pi^-\pi^0\pi^0$ production by the JADE collaboration.[27] The $\pi^\pm\pi^0$ mass combinations have been required to fall in a $\rho^\pm$ mass band so that their measurement is essentially an upper limit for $\rho^+\rho^-$ production. The prediction for a single isospin 2 resonance as shown in Fig. 23 is clearly ruled out.

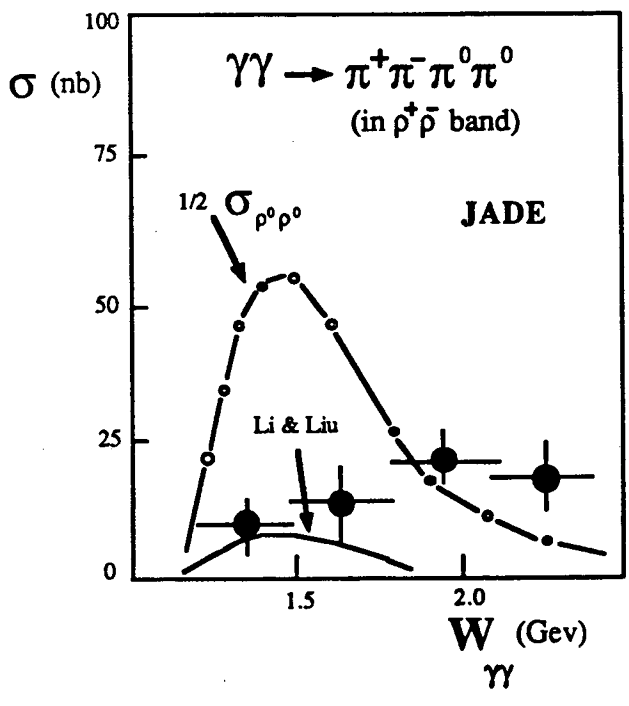


Fig. 23
Cross section for $\pi^+\pi^-\pi^0\pi^0$ production from the JADE collaboration.

Predictions based on interfering four quark resonances[29),30)] which interfere constructively in the $\rho^0\rho^0$ channel and destructively in the $\rho^+\rho^-$ are consistent with the measurements. Figure 23 displays a prediction of $\rho^+\rho^-$ production from Li and Liu.[30)]

5.2 $K^+K^-\pi^+\pi^-$ Production

Measurements of $K^+K^-\pi^+\pi^-$ production have been made by the TPC/Two Gamma and TASSO collaborations. The TPC/Two Gamma results have been published.[31)] Final results from the TASSO group have been submitted[32)] to this conference. The two experiments report different topological cross sections. Subtracting TASSO's measured $\phi\pi^+\pi^-$ cross section from their topological cross section, one observes that the results from the two experiments, shown in Fig. 24, are in good agreement.

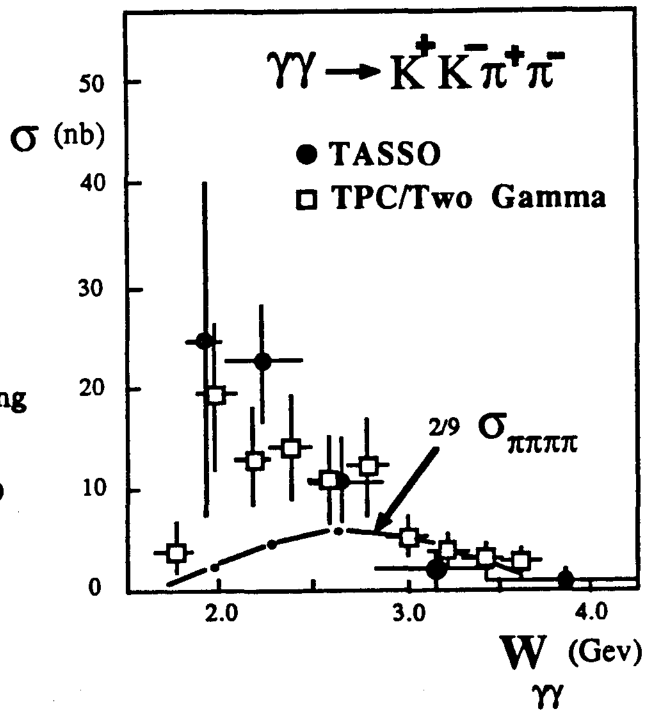


Fig. 24
Topological cross section for $K^+K^-\pi^+\pi^-$ production, excluding $\phi\pi^+\pi^-$ production, from the TPC/Two Gamma and TASSO groups.

Using the measurements of multipion production discussed in Section 3, assuming vector meson dominance in photon-photon interactions and using the expected couplings of the photon to ρ, ω and ϕ, one can construct an "Experimentalist's Guide" for comparing various reaction rates. The comparison of vector meson pair production in Section 4.1 is one example. To compare measurements with one vector meson or multiprongs, one uses the square of the photon-vector meson couplings which may be entering into the scattering process. Thus for the non-resonant contribution to $K^+K^-\pi^+\pi^-$, one can take 2/9 times the measured $\pi^+\pi^-\pi^+\pi^-$ cross section as a guide, assuming that in the former reaction a $\gamma - \phi$ coupling enters while a $\gamma - \rho^0$ coupling enters in the latter. This simple "Experimentalist's Guide", shown in Fig. 24, has been shifted by twice the K-π mass difference. One might say that the data at higher mass, $W_{\gamma\gamma} > 3.0$ GeV/c^2, are consistent with this simple comparison, while the data at lower mass are a factor of 2 - 3 above this non-resonant prediction.

Vector meson pair production ($\rho^0\phi, \phi\phi$, and K^*K^*) has been searched for by both groups in the four-prong final states with at least one K^+K^- pair. While no signal for vector meson pair production has been obtained, ϕ and K^* meson production have been observed. The upper limits for $\rho^0\phi$ and $\phi\phi$ from the TASSO collaboration are shown in Fig. 25. If we assume that $\rho^0\phi$ and $\phi\phi$ scattering is similar to $\rho^0\rho^0$ scattering then one might expect that the peak cross sections would be at $W_{\gamma\gamma} \sim M_\rho + M_\phi \simeq 1.7$ GeV/c^2 and $W_{\gamma\gamma} \sim 2M_\phi \simeq 2$ GeV/c^2 for $\rho^0\phi$ and $\phi\phi$ production, respectively, since the peak in the $\rho^0\rho^0$ cross section is at $W_{\gamma\gamma} \sim 2M_\rho \simeq 1.5$ GeV/c^2. The resulting cross sections might appear as the curves shown in Fig. 25.

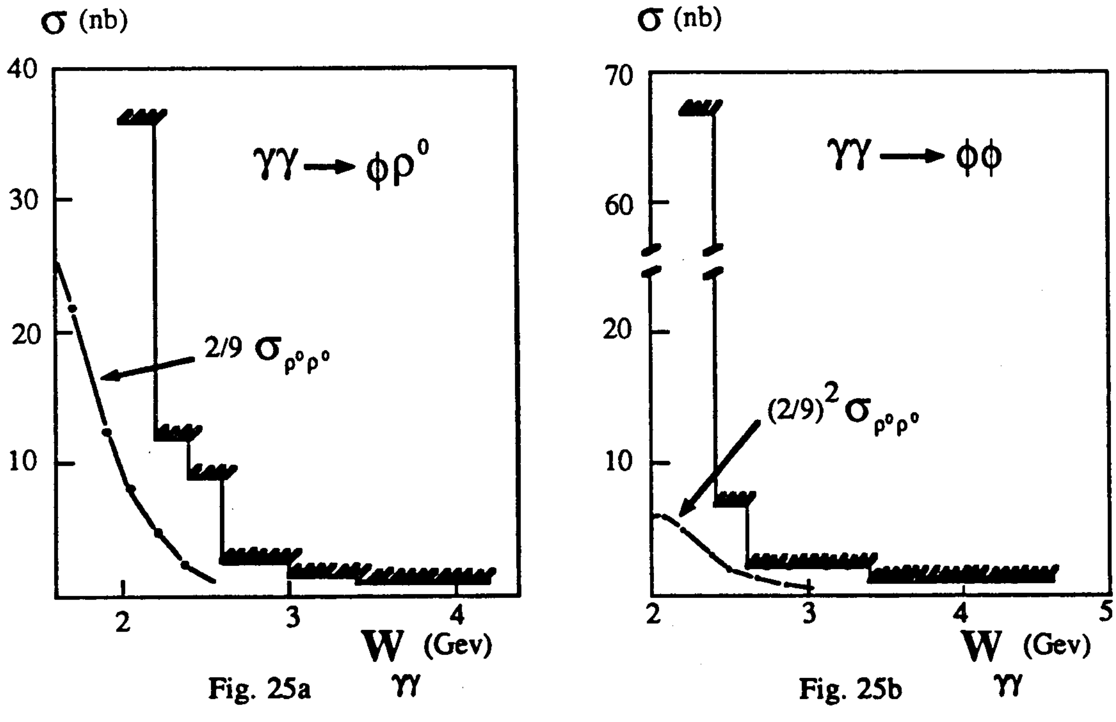


Fig. 25

Upper limits for $\rho^0\phi$ and $\phi\phi$ production from the TASSO collaboration.

One observes that the present upper limits do not exclude the simple prediction of this "Experimentalist's Guide". It is important to note that low mass $\rho^0\phi$ and $\phi\phi$ as well as high energy diffractive ϕ production is difficult to measure since the Q value for $\phi \rightarrow KK$ is small. Measurement of $\phi \rightarrow \pi^+\pi^-\pi^0$ is hampered by the identification of π^0's and combinatorial backgrounds.

Both the TPC/Two Gamma and TASSO groups have found a large fraction of $K^{*0}K^{\pm}\pi^{\mp}$ production in the exclusive $K^+K^-\pi^+\pi^-$ final state sample. The $K^{\pm}\pi^{\mp}$ mass spectrum from the TASSO measurement is shown in Fig. 26 and the measured fractions are given in Table 1.

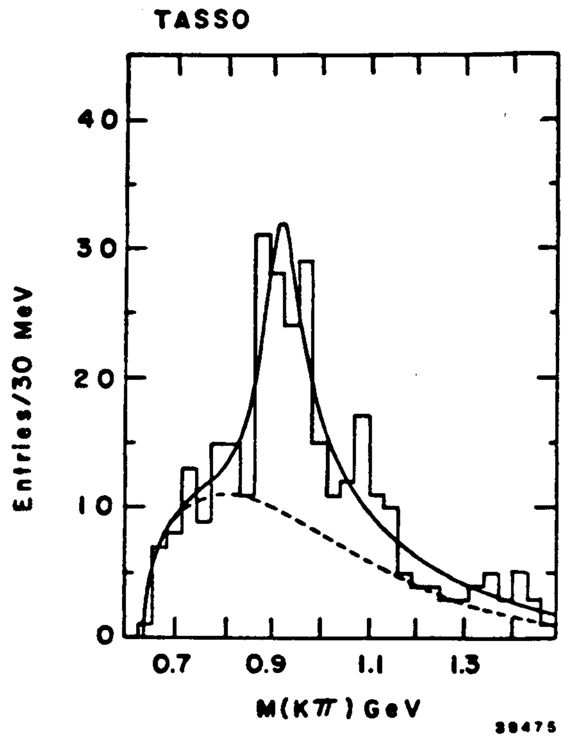


Fig. 26
$K^{\pm}\pi^{\mp}$ mass spectrum from the TASSO measurement of $K^+K^-\pi^+\pi^-$.

Table 1
Measured fraction of $K^{*0}K^{\pm}\pi^{\mp}$ events within the $K^+K^-\pi^+\pi^-$ event samples.

Experiment	$W_{\gamma\gamma}$ *range*	$K^{*0}K^{\pm}\pi^{\mp}$ *fraction*
TPC/Two Gamma		$(42 \pm 13)\%$
TASSO	$1.8 < W_{\gamma\gamma} < 2.0$	$(41 \pm 24)\%$
	$2.0 < W_{\gamma\gamma} < 2.4$	$(57 \pm 14)\%$

The measured cross section for $K^{*0}K^{\pm}\pi^{\mp}$ from the TASSO group is shown in Fig. 27. One should note that the cross section peaks at low mass and is small above 3.0 GeV/c^2. If one compares to the topological cross section of Fig. 25 and the prediction for the non-resonant $KK\pi\pi$ production, one observes that the excess at low mass is due to $K^{*0}K\pi$ production and the "Experimentalist's Guide" appears to be in good agreement with the non-resonant $KK\pi\pi$ yield.

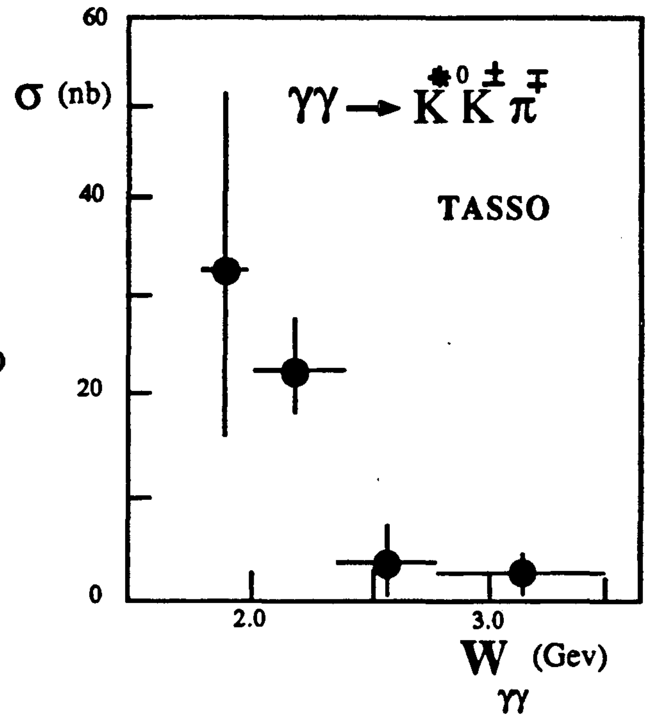


Fig. 27
Cross section for $K^{*0}K^{\pm}\pi^{\mp}$ production from the TASSO collaboration.

The large fraction of events with K^* is surprising. One might try to explain K^* production with kaon exchange as in the diagram shown in Fig. 28.

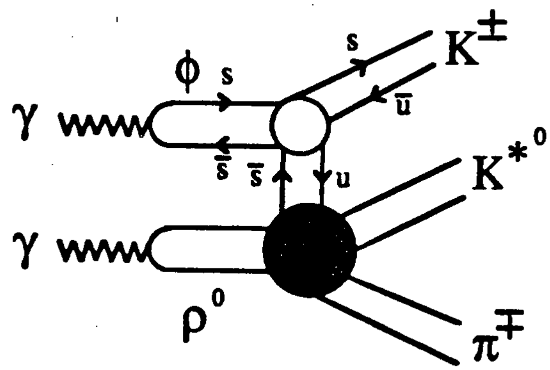


Fig. 28
Kaon exchange contribution to K* production in two photon reactions.

A simple check of the $K^*\pi$ system for an intermediate resonance, such as $Q_1(1280)$ or $Q_2(1400)$ did not show a clear resonance enhancement.[33]

Upper limits for $K^*\bar{K}^*$ have been provided by both the TPC/Two Gamma and TASSO collaborations. The results from the TASSO group are shown in Fig. 29. The present upper limits do not exclude recent $Q^2\bar{Q}^2$ models[29),30)]; for example, the curve shown in Fig. 29 is the prediction from Li and Liu.[30]

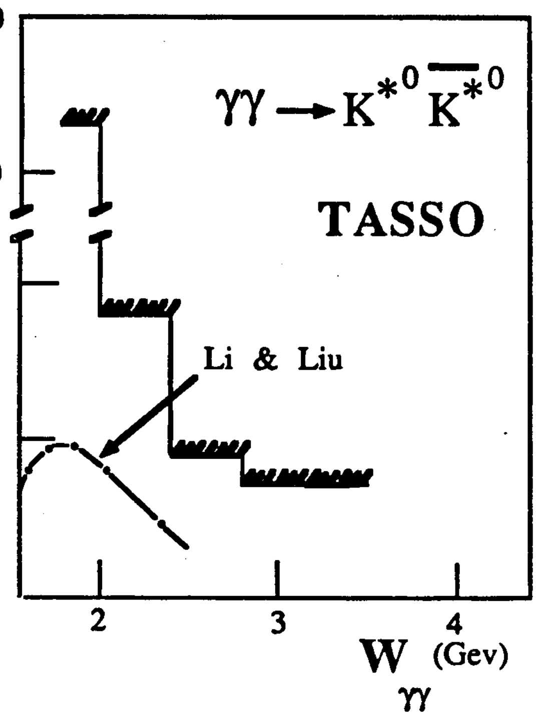


Fig. 29
Upper limits for $K^*\bar{K}^*$ production from TASSO and an estimate for $Q^2\bar{Q}^2$ contribution[30].

5.3 Single Neutral Vector Meson Production

In their measurements of $K^+K^-\pi^+\pi^-$ production, both the TPC/Two Gamma and TASSO collaborations have observed clear evidence for $\phi\pi^+\pi^-$ production. The result from TASSO is shown in Fig. 30. A simple prediction based on our "Experimentalist's Guide" and the measured $\rho^0\pi^+\pi^-$ cross section from Fig. 17 is in reasonable agreement with the $\phi\pi^+\pi^-$ measurement and suggests that the vector meson scattering processes are similar.

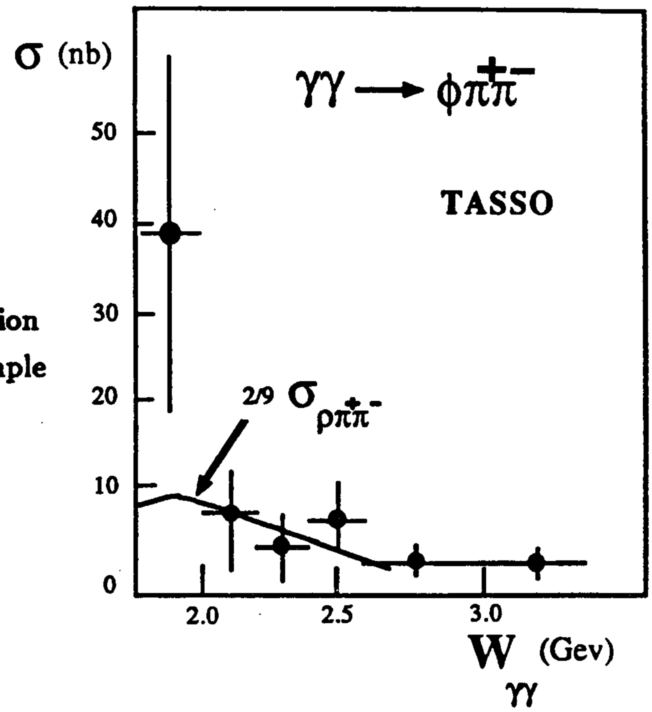


Fig. 30
Cross section for $\phi\pi^+\pi^-$ production from the TASSO group and a simple prediction based on an "Experimentalist's Guide".

It is interesting to note that neither experiment reports any evidence of $\rho^0K^+K^-$ production in their $K^+K^-\pi^+\pi^-$ samples. One can make an estimate for $\rho^0K^+K^-$ production of

$$\sigma^{peak}_{\rho^0K^+K^-} \sim \frac{2}{9}\sigma^{peak}_{\rho^0\pi^+\pi^-} \simeq 10nb. \tag{9}$$

The TPC/Two Gamma collaboration has published[31] a $\pi^+\pi^-$ mass spectrum which doesn't show any clear evidence for a ρ^0 peak; however, due to the large width of the ρ and limited statistics, an upper limit has not been given. At present, the limited statistical samples also have not yielded a measurement of ϕK^+K^- which one would like to compare to $\rho^0K^+K^-$.

One of the most exciting results in the study of photon-photon scattering presented at this conference has been the measurement of exclusive ω production by the ARGUS collaboration.[34] Their preliminary topological cross section for $\omega\pi^+\pi^-$ production is shown in Fig. 31. A simple estimate for $\omega\pi^+\pi^-$ cross section of $\sigma_{\omega\pi^+\pi^-} \simeq (1/9)\ \sigma_{\rho^0\pi^+\pi^-}$ using the expected photon vector meson coupling ratio of $(\gamma-\omega)\ /\ (\gamma-\rho^0) \simeq 1/3$ is shown as a solid curve in Fig. 31.

The ARGUS group has studied the $\pi^+\pi^-$ system and have given a preliminary result that for $W_{\gamma\gamma}$ greater than 1.7 GeV/c^2 the final $\omega\pi^+\pi^-$ system is essentially pure $\omega\rho^0$. An estimate of $\sigma_{\rho^0\omega} \simeq (1/9)\ \sigma_{\rho^0\rho^0}$ is also shown in Fig. 31. It is surprising that the cross section peaks at $W_{\gamma\gamma} \sim 1.9$ GeV/c^2 and not nearer threshold

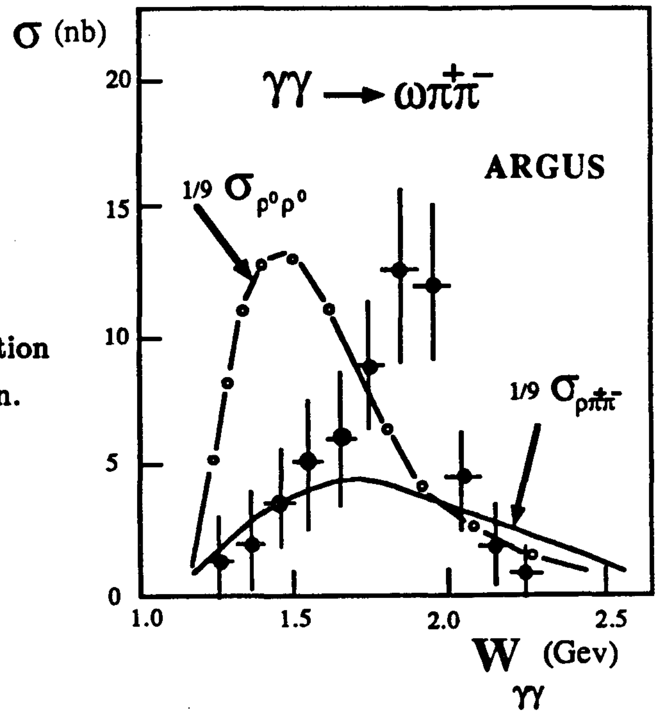


Fig. 31
Cross section for $\omega\pi^+\pi^-$ production from the ARGUS collaboration.

as in $\rho^0\rho^0$ production, and that there is no significant $\omega\pi^+\pi^-$ production above $W_{\gamma\gamma} \sim 2.2$ GeV$/c^2$. This preliminary result seems to suggest a resonance in the $\rho^0\omega$ channel at $W_{\gamma\gamma} \sim 1.85$ GeV$/c^2$. Other experiments, such as CELLO and TPC/Two Gamma, have $\rho^0\omega$ analysis groups which soon should provide confirmation of these results.

5.4 Comparison to QCD Predictions

The perturbative QCD description of meson pair production by Brodsky and Lepage[3)] predicts the yield of vector meson pairs $(\rho^0\rho^0, \rho^+\rho^-, \rho^0\omega, ...)$ at large angles. Their calculation, which uses the meson decay constant to relate vector meson production to pion production, is not very sensitive to the uncertainties in the meson distribution amplitudes. Final state helicity dependence of the cross section offers an opportunity to study the helicity structure of the underlying hard scattering amplitude, however recent experiments have not reported measurements of the final state polarization for vector meson production. Summing over the helicity cross section predictions of Ref. 3, one obtains the predictions shown in Fig. 32.

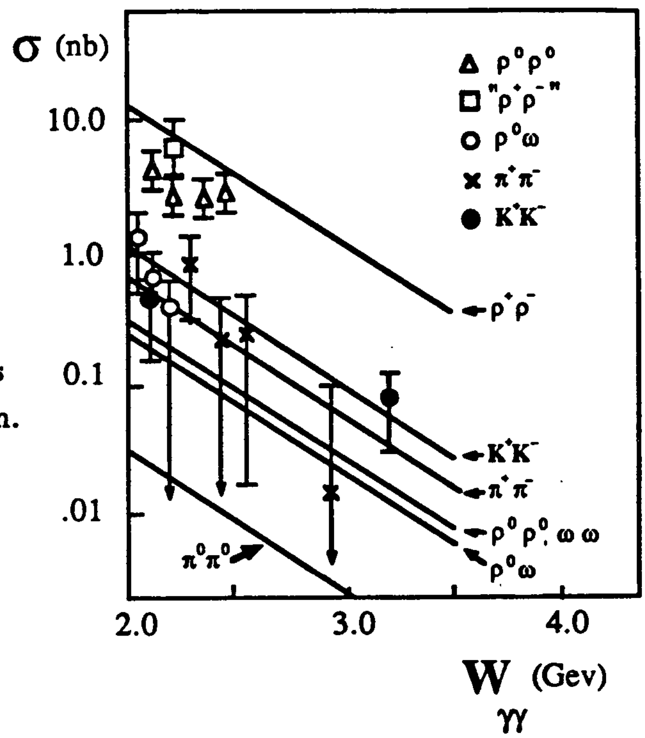


Fig. 32
Large angle ($|\cos\theta^*| < 0.3$) cross sections for meson pair production.

The data points shown in Fig. 32 are for high mass production of $\pi^+\pi^-$ and K^+K^- [6], $\rho^0\rho^0$ [18], $\rho\omega$ [34] and includes the measurement of $\pi^+\pi^-\pi^0\pi^0$ production with the ρ mass band cut on the $\pi^\pm\pi^0$ masses.[27] Clearly, one would like to improve the statistics of these measurements and extend the measurements to higher mass in order to make a more precise comparison to the QCD predictions.

6. SUMMARY

Several interesting new results on exclusive two photon processes were submitted to this conference. From the MARK II and TPC/Two Gamma collaborations it has been found that at $W_{\gamma\gamma} \simeq 2.5$ GeV/c^2 the measurements of large angle $\pi^+\pi^-$ and K^+K^- production are in reasonable to good agreement with perturbative QCD predictions. The TASSO, JADE and TPC/Two Gamma groups have measured $p\bar{p}$ production to be an order of magnitude above the highest perturbative QCD prediction at low invariant mass, $W_{\gamma\gamma} \simeq 2.5$ GeV/c^2. The perturbative QCD calculations predict a large yield of $\Delta^{++}\overline{\Delta^{++}}$ pairs; however, although the measurements by the TASSO and TPC/Two Gamma collaborations give a large $p\bar{p}\pi^+\pi^-$ production cross section, no clear evidence for baryon pair production other than $p\bar{p}$ has been obtained.

The measurements of $K^+K^-\pi^+\pi^-$ production by the TPC/Two Gamma and TASSO groups have shed light on our understanding of vector meson pair production. The rough agreement between multipion and $K^+K^-\pi^+\pi^-$ measurements using a simple "Experimentalist's Guide" suggests that coupling of the initial photons to vector mesons may occur at the initial stage of the underlying process. New results from the ARGUS collaboration on $\rho^0\omega$ production offers a chance to better understand the enhancement in the $\rho^0\rho^0$ channel and to study the detailed interactions of photons with hadrons at low Q^2.

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