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1 INTRODUCTION

In view of the limited time I will confine myself mainly to the subject of $\gamma\gamma \to$ V V' [1], with some mention at the end about $\gamma\gamma \to B\bar{B}$.

It is customary in these talks to point out what new information do we have since the last Rochester conference. At Berkeley we had only one reaction well measured,$\gamma\gamma \to \rho^0\rho^0$, preliminary results of $\gamma\gamma \to \rho^0\ \omega$, and some upper limits[2]. Today we have measurements of six out of the possible 9 V V' combinations and upper limits on the remaining three:

- $\gamma\gamma \to \rho^0\rho^0$ — CELLO, MARK II, PLUTO, TASSO, TPC/2γ[3]
- $\gamma\gamma \to \rho^0\omega$ — ARGUS, CELLO, TPC/2γ[4]
- $\gamma\gamma \to \rho^0\phi(u.l.)$ — ARGUS, TASSO, TPC/2γ[5]
- $\gamma\gamma \to \omega\omega$ — ARGUS[6]
- $\gamma\gamma \to \omega\phi(u.l.)$ — ARGUS[7]
- $\gamma\gamma \to \phi\phi(u.l.)$ — ARGUS, TASSO, TPC/2γ[8]
- $\gamma\gamma \to \rho^+\rho^-$ — ARGUS, CELLO[9]
- $\gamma\gamma \to K^{*0}\bar{K}^{*0}$ — ARGUS[10]
- $\gamma\gamma \to K^{*+}\bar{K}^{*-}$ — ARGUS[11]

Let us now say a few words about each reaction.

2 $\gamma\gamma \to \rho^0\rho^0$

The by now well known low mass enhancement below the nominal $\rho^0\rho^0$ threshold (Fig. 1) was first observed by the TASSO group[3d]. It founded the dispute between the traditional non-exotic interpretation that this enhancement can be explained by t-channel factorization[12], and the exotic explanation that this enhancement is the result of a constructive interference between I=0 and I=2 $q\bar{q}q\bar{q}$ states [13]. Both models give a good description of the data, but I would like to turn your attention to the very low cross section measured for this reaction above 2 GeV. We will return to this point in section 8.

How is this and other V V' cross sections obtained ? The distributions are fitted to a 3-parameter fit of a sum of non-interfering contributions in each W interval. For the present reaction one uses a$\cdot(\gamma\gamma \to \rho^0\rho^0\ )$ + b$\cdot(\gamma\gamma \to \rho^0\pi^+\pi^-\ )$+c$\cdot(\gamma\gamma \to \pi^+\pi^+\pi^-\pi^-)$, where a, b and c give the percentage of each process leading to the observed final state. For each of the three processes a model is assumed which describes it. For the $\rho^0\rho^0$ final state the

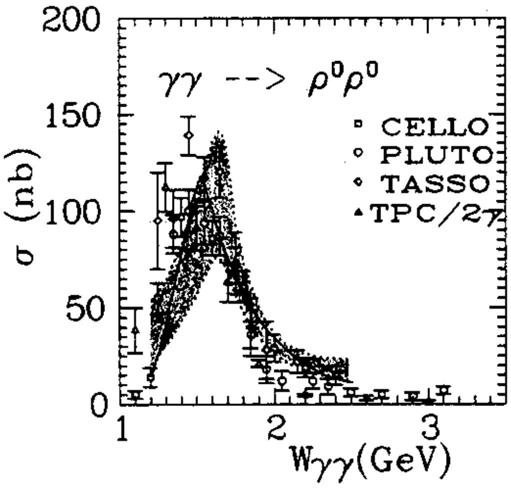


Figure 1: A compilation of $\gamma\gamma \rightarrow \rho^0\rho^0$ cross sections[3]. The shaded region is the expectations of the t-channel factorization model[12] and the solid curve is that of a 4-quark interpretation[13]

matrix element includes two relativistic Breit-Wigner shape resonances and some angular correlations. For the $\rho^0\pi^+\pi^-$ final state, only one Breit-Wigner is used and the remaining $\pi^+\pi^-$ are produced isotropically[3d]. A compilation of the $\rho^0\pi^+\pi^-$ cross section values thus obtained as function of W can be seen in Fig. 2, and shows a possible enhancement around 1.9-2.0 GeV, with an appreciable cross section above 2 GeV[14]. In fact, the $\rho^0\pi^+\pi^-$ cross section is even higher than the $\rho^0\rho^0$ cross section in this region.

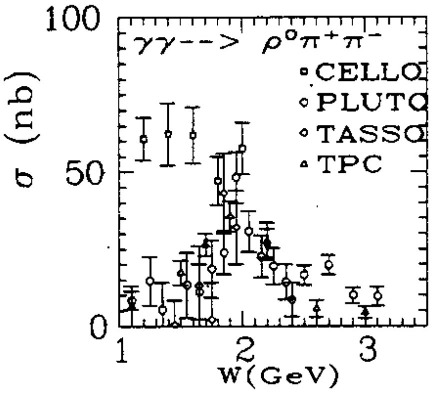


Figure 2: A compilation of $\gamma\gamma \rightarrow \rho^0\pi^+\pi^-$ cross sections[3]

At this point I would like to sound a criticism that was first pointed out by ACHASOV and SHESTAKOV[15], and concerns all $\gamma\gamma$ reactions in which one neutral vector meson is produced. Let us use the $\rho^0\pi^+\pi^-$ as an example. The charge conjugation of $\rho^0\pi^+\pi^-$ has to be positive. Since the ρ^0 is an eigenstate of C one can write:

$$C(\rho^0\pi^+\pi^-) = C(\rho^0)\cdot C(\pi^+\pi^-) = -C(\pi^+\pi^-) = +$$

Since the charge conjugation of a particle-antiparticle system is given by $(-)^{l+s}$,

$$C(\pi^+\pi^-) = (-)^l = -$$

which means that l has to be odd, and at these low energies we take l=1. Using the relation connecting G, C and I

$$G(\pi^+\pi^-) = C(\pi^+\pi^-)\cdot(-)^I$$

one restricts the isospin to I=1. Therefore the quantum numbers of the recoiling $\pi^+\pi^-$ are

$$I^G(J^P)C[\pi^+\pi^-] = 1^+(1^-)-$$

which are exactly the quantum numbers of a ρ^0. What then is the meaning of a $\rho^0\pi^+\pi^-$ final state in which the $\pi^+\pi^-$ mass is generally less than 1.2 GeV and has exactly the quantum numbers of a ρ^0 ? Thus it seems that the ansatz of 3 non-interfering processes may not be a good one and one may have to reanalyze the data, taking into account the restrictions on the recoiling $\pi^+\pi^-$. It is not clear how this will change the results, but it has to be done.

The same arguments hold for $\omega\pi^+\pi^-$ and $\phi\pi^+\pi^-$. Some restrictions are obtained also for the case $\omega\pi^+\pi^-\pi^0$ and $\phi\pi^+\pi^-\pi^0$. It does not hold for vector mesons which are not eigenstates of C, like $\rho^\pm$ or K^*. With this in mind, let us proceed to the other reactions.

3 $\gamma\gamma \rightarrow \rho^0\omega$

A compilation of the cross section measurements[4] of the reaction $\gamma\gamma \rightarrow \omega\pi^+\pi^-$ is shown in Fig. 3. The three measurements are consistent within error, though the CELLO data[4b] have a somewhat different shape. All three groups can not distinguish between $\omega\pi^+\pi^-$ and

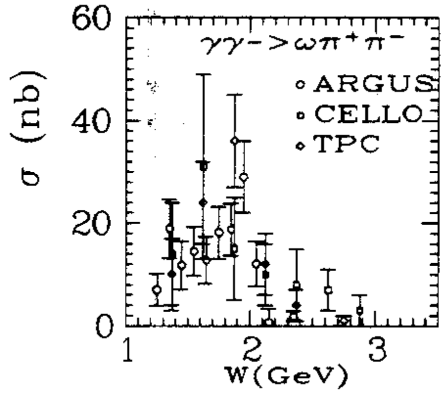


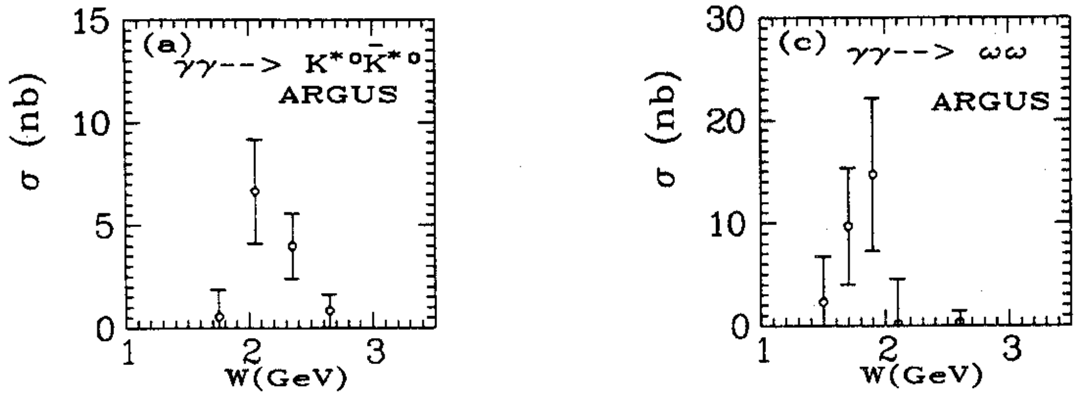
Figure 3: A compilation of $\gamma\gamma \rightarrow \omega\pi^+\pi^-$ cross sections[4]

$\omega\rho^0$ final states, but ARGUS[4a] and TPC/2γ[4c] claim that most of the $\omega\pi^+\pi^-$ is in fact $\omega\rho^0$ final state. The data show an enhancement around 1.9-2.0 GeV, similar to that seen in $\rho^0\pi^+\pi^-$,which cannot be explained by the t-channel factorization model, nor by the 4-quark model with the parameters as tuned for the $\rho^0\rho^0$ final state. The TPC/2γ group can get a good fit of the 4-quark model to their data by changing the parameters of the model[4c].

4 $\gamma\gamma \rightarrow \omega\omega$, $\gamma\gamma \rightarrow K^{*0}\bar{K}^{*0}$, $\gamma\gamma \rightarrow K^{*+}\bar{K}^{*-}$

The reason I grouped these three reactions together is that they have been measured exclusively only by the ARGUS group. Note the similar W behaviour of all three reactions shown in Fig. 4. Note also the large ratio of the cross section of $K^{*+}\bar{K}^{*-}$ to that of $K^{*0}\bar{K}^{*0}$, which can be explained by the 4-quark model and by a dual QCDmodel[16], however the absolute predictions are an order of magnitude smaller than the data. A one-kaon-exchange model[15], which gives a good description of the $K^{*0}\bar{K}^{*0}$ reaction, predicts the $K^{*+}\bar{K}^{*-}$ to be about 5.3 smaller than the $K^{*0}\bar{K}^{*0}$ - in contradiction to the data.

The predictions of the t-channel factorization[12] exceed the $\omega\omega$ data above 2 GeV, where, according to ARGUS, there is a large contribution of an $\omega\pi^+\pi^-\pi^0$ final state. One should however keep in mind that the charge conjugation restriction was not taken into account. This could also be the reason why a one-pion exchange calculation[15] has some problems fitting the data in that region.



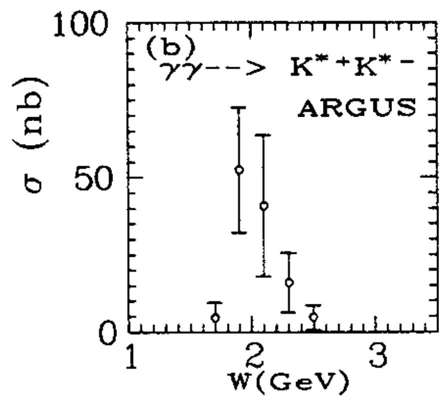


Figure 4: Cross sections for (a) $\gamma\gamma \to K^{*0}\bar{K}^{*0}$ [10], (b) $\gamma\gamma \to K^{*+}\bar{K}^{*-}$ [11] , and (c) $\gamma\gamma \to \omega\omega$[6]

5 $\gamma\gamma \to \rho^+\rho^-$

Until recently only the JADE upper limits existed for the reaction $\gamma\gamma \to \rho^+\rho^-$ [17]. They were very important since they ruled out the interpretation of a single s-channel resonance decaying into $\rho\rho$. The new measurements of ARGUS[9a] and CELLO[9b], shown in Fig. 5, agree well with each other and confirm the JADE upper limits. None of the presently

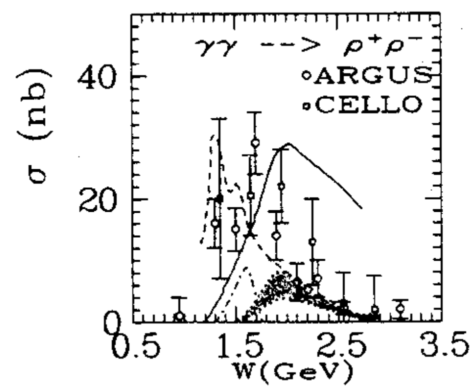


Figure 5: Cross sections for the reaction $\gamma\gamma \to \rho^+\rho^-$ [9]. Theory: t-channel factorization[12] (shaded), 4-quark [13] (dashed), 4-quark [18] (dashed-dot) and dual QCD[16] (full line)

existing models can explain the behaviour of the data over the whole presently available W range.

6 $\gamma\gamma \rightarrow \rho^0\pi^+\pi^-$, $\omega\pi^+\pi^-, \omega\omega$, $K^{*0}\bar{K}^{*0}$, $K^{*+}\bar{K}^{*-}$, $\rho^+\rho^-$

I have plotted again, side by side, the cross section of all these six reactions in Fig. 6, in order to point out their similar W behaviour and the enhancement they all show around 1.9-2.0 GeV. A detailed study of this region is needed to confirm one or more resonance states.

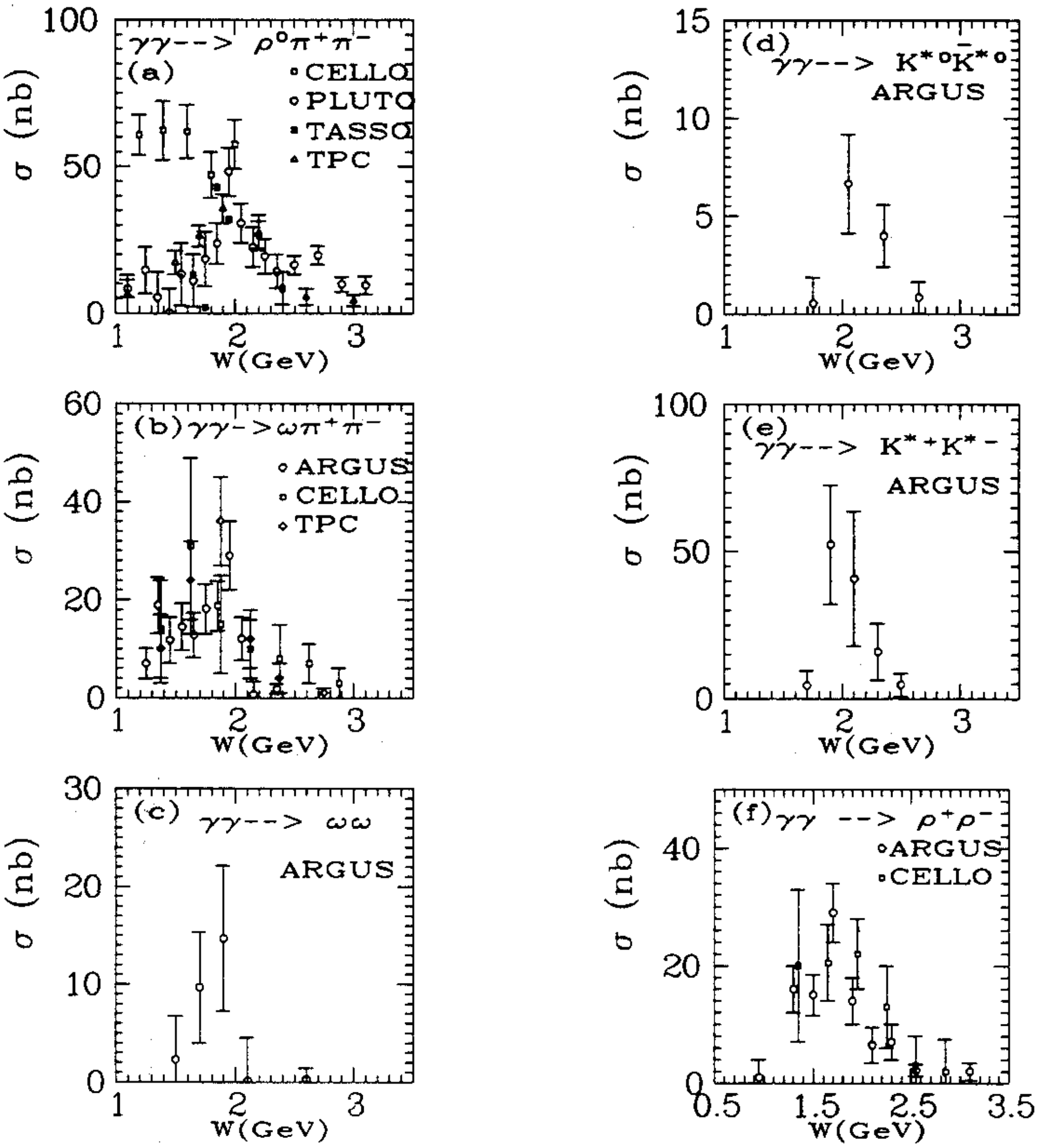
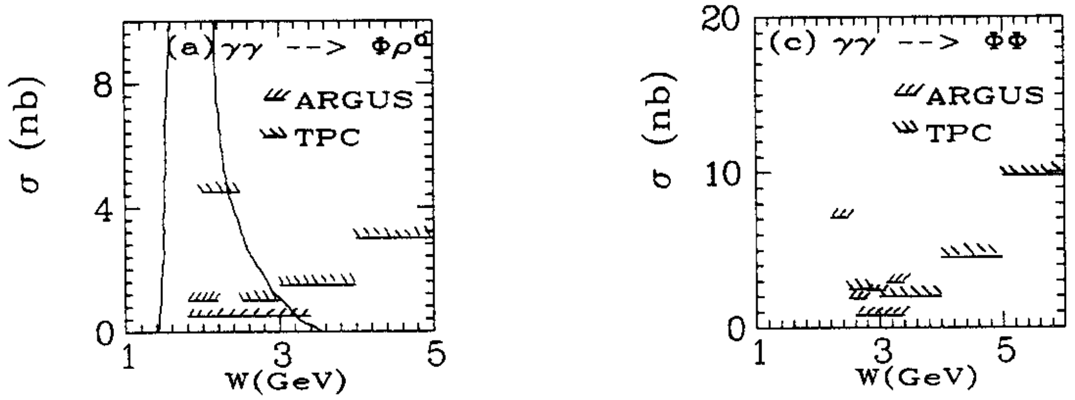


Figure 6: Cross sections for (a) $\gamma\gamma \rightarrow \rho^0\pi^+\pi^-$, (b) $\gamma\gamma \rightarrow \omega\pi^+\pi^-$, (c) $\gamma\gamma \rightarrow \omega\omega$, (d) $\gamma\gamma \rightarrow K^{*0}\bar{K}^{*0}$,(e) $\gamma\gamma \rightarrow K^{*+}\bar{K}^{*-}$, and (f) $\gamma\gamma \rightarrow \rho^+\rho^-$

Note that a similar enhancement is observed in this energy region in some $J/\psi \rightarrow \gamma VV'$ decays[19].

7 $\gamma\gamma \to \phi\rho^0$, $\gamma\gamma \to \phi\omega$, $\gamma\gamma \to \phi\phi$

The ϕ meson does not show, at the present luminosities, associated production with another vector meson. Only upper limits, shown in Fig. 7, have been measured so far[5,7,8], the best



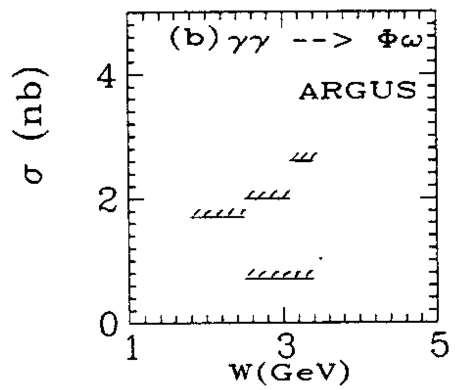


Figure 7: Upper limits for (a) $\gamma\gamma \to \phi\rho^0$, (b) $\gamma\gamma \to \phi\omega$, and (c) $\gamma\gamma \to \phi\phi$. The solid curve in (a) is the prediction of a 4-quark model[13]

one given by ARGUS. ARGUS is also the only experiment to give any information on the $\phi\omega$ reaction. The 4-quark model[13] has some difficulty with the $\phi\rho^0$ upper limits, shown in Fig. 7a. However here too no C restriction has been considered in the data analysis. All other models are consistent with the data.

8 The OPTICAL CONNECTION

Are all the data we have seen up to now consistent with other $\gamma\gamma$ measurements ? One can check such a consistency by using the $\gamma\gamma$ hadronic total cross section, which can be connected through the optical model and the Vector Dominance model to the reactions $\gamma\gamma \to V^0V'^0$[20]:

$$\sigma_T(\gamma\gamma) = \alpha\sqrt{\pi}\sum_{VV'}\left(\frac{4\pi}{\gamma_V^2}\right)\left(\frac{4\pi}{\gamma_{V'}^2}\right)[B_{VV'}\cdot\sigma(\gamma\gamma \to V^0V'^0)]^{\frac{1}{2}}$$

Figure 8 shows the published $\gamma\gamma$ total cross sectioned measurements of PLUTO[21] and TPC/2γ[22]. The dotted line is the prediction $\sigma =$ 187 + 702/W using a factorization model[23]. I have subtracted from this expression the point-like contribution, using the QPM[24], and have obtained the solid line. The open squares are the contributions to the total cross section coming from the $V^0V'^0$ measurements, using the optical model. One gets indeed a consistent picture up to 2 GeV. Between 2 and 3 GeV however, the measured $V^0V'^0$ cross sections are too low and fail the consistency check. This deficiency may be connected

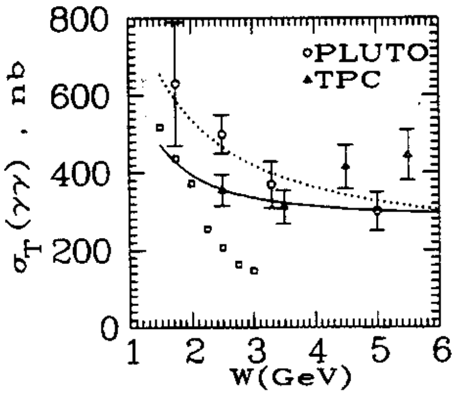


Figure 8: $\gamma\gamma$ total hadronic cross section (see text)

with the criticism discussed in section 2, where the determination of the $\rho^0\pi^+\pi^-$ cross section was evaluated.

Another possible solution to the inconsistency could be that we are missing some $V^0V'^0$ states above 2 GeV. Since the main contribution to $\sigma_T(\gamma\gamma)$, using the optical model, comes from $\rho^0V'^0$ final states, the first reaction that comes in mind is $\gamma\gamma \to \rho^0\rho'^0(1600)$[20]. The ρ'^0 decays mainly through $\rho^0\pi^+\pi^-$, one should look for the reaction $\gamma\gamma \to \rho^0\rho'^0(1600) \to \rho^0\rho^0\pi^+\pi^- \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$. Both ARGUS[25] and CELLO[26] have measured this final state, shown in Fig. 9, and get very good agreement with each other. One can indeed see

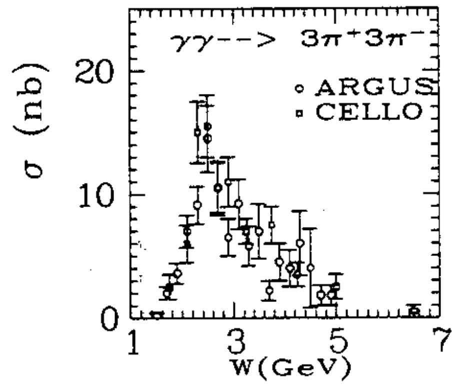


Figure 9: Cross section of the reaction $\gamma\gamma \to 3\pi^+3\pi^-$[25,26]

that the cross section has a sharp rise just at the $\rho^0\rho'^0(1600)$ threshold. The CELLO group searched for this final state and the preliminary indications are promising[26]. They find a clear ρ^0 signal and indication for $\rho^0\rho^0\pi^+\pi^-$ production. Since both $\rho'^0(1600)$ and the ρ^0 are wide resonances, it is difficult to claim a signal and this channel is still under study.

9 $\gamma\gamma \to p\bar{p}$, $\gamma\gamma \to p\bar{p}\pi^+\pi^-$

There are some new measurements of $\gamma\gamma \to p\bar{p}$ and $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ by ARGUS[27] and TPC/2γ[28]. The theories are still struggeling with these reactions. There is an attempt to get the correct order of magnitude for the $p\bar{p}$ final state using a quark-scalar diquark scheme[29], which indeed is an improvement, but the predictions are still too low. The measured $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ cross sections of ARGUS and TPC/2γ agree well with each other and with earlier measurements of the TASSO group[30]. The ARGUS group sees for the first time a clear Δ^{++} and $\bar{\Delta}^{--}$ signal in $\gamma\gamma$ reactions, however not in association with each other. Thus the ratio of $\Delta^{++}\bar{\Delta}^{--}/p\bar{p}$ can be obtained only as an upper limit and is less than 1 around 3 GeV.

10 SUMMARY and CONCLUSIONS

- We have now information on all the $\gamma\gamma \rightarrow$ VV' reactions and all detectors agree with each other's measurements. However there may be a need to reanalyze some of the reactions in order to take into account the restrictions evolving from charge conjugation conservation on the three-body final states.
- No single model can explain all the data. We will probably have to use some hybrid models to get a clear picture of all the channels.
- Is there one or more states around 1.9-2.0 GeV that can explain the enhancement seen in this region in different final states ?
- Where are the missing $V^0V^{0\prime}$ states ? We need them in order to get a consistent picture with the total $\gamma\gamma$ hadronic cross section measurements. Do we see a $\rho^0\rho'^0(1600)$ final state in the $3\pi^+3\pi^-$ final state ?
- All measurements of $\gamma\gamma \rightarrow B\bar{B}$ agree with each other and there is a first signal of Δ^{++} and $\bar{\Delta}^{--}$ production in $\gamma\gamma$ reactions, though not in association with each other.

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