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ρ^0 Production in the reaction $\gamma\gamma \to 3\pi^+ 3\pi^-$ and search for $\gamma\gamma \to \rho^0 \rho^0$ (1700)

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Abstract. We have studied the ρ^0 production rate in the reaction $\gamma\gamma \to 3\pi^+ 3\pi^-$ in the energy range $1.6 \leqq W_{\gamma\gamma} \leqq 7.5$ GeV with the CELLO detector at PETRA. Our analysis points to a substantial yield of $\rho^0\rho^0\pi^+\pi^-$ events in particular at $W_{\gamma\gamma} > 4.0$ GeV. We give cross sections for the $\rho^0 2\pi^+ 2\pi^-$ and $\rho^0\rho^0\pi^+\pi^-$ final states and calculate upper limits for the reaction $\gamma\gamma \to \rho^0\rho^0(1700) \to \rho^0\rho^0\pi^+\pi^-$.

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Table 1. Number of events, mean number of ρ^0's per event and the goodness of the fit in each $W_{\gamma\gamma}$ interval

$W_{\gamma\gamma}$ [GeV]	N^{events}	$\tilde{N}^{\rho^0}$	$\frac{\chi^2}{\text{NDF}}$
2.0–3.0	246	1.41 ± 0.22	1.05
3.0–4.0	157	0.89 ± 0.28	0.75
4.0–7.5	48	2.16 ± 0.41	1.60

The vector dominance model (VDM) provides a good overall description of inclusive $\gamma\gamma$ reactions; however, the model faces difficulties with the exclusive $\gamma\gamma$ processes, in particular, with $\gamma\gamma \to \rho^0\rho^0$. The study of exclusive final states in $\gamma\gamma$ reactions has proceeded mainly in two directions: formation of s-channel resonances leading to low multiplicity final states [1], and vector meson pair production in the 4 and 5 body final states [2]. Studies of the latter found prolific associated production of the vector mesons – $\rho\rho$, $\omega\omega$, $\rho^0\omega$ and K^*K^*. Disagreement between VDM predictions and the data on $\gamma\gamma \to VV'$ processes led to the formulation of the t-channel factorization scheme [3] and to the four quark bound state model [4]. However none of these models provide a comprehensive description of the $\gamma\gamma \to VV'$ processes [5].

It is of interest to extend the search for VV' final states to higher multiplicity channels where heavier vector mesons should become accessible [6]. We present here the results of a search for the exclusive channel $\gamma\gamma \to \rho^0\rho^0(1700)$, studying the ρ^0 content in the reaction $\gamma\gamma \to 3\pi^+3\pi^-$. The global properties of this channel have been presented in a previous paper [7].

The data consisting of an integrated luminosity of $86\ \text{pb}^{-1}$, were taken with the CELLO detector at the PETRA e^+e^- storage ring at a center of mass energy of 35 GeV. The setup of the experiment and the data selection have been described elsewhere [7].

The untagged $3\pi^+3\pi^-$ events that were selected are distributed in $W_{\gamma\gamma}$ as listed in Table 1. We estimate the non-exclusive background to be about $(18 \pm 7)\%$, based on studies of the missing p_T distributions and on Monte Carlo studies of feed down from higher multiplicity channels. An additional background of about 2% due to K_S^0 contamination was estimated from a secondary vertex search. From this study we were also able to obtain an estimate for the charged kaon contamination of about 3% [7].

The number of ρ^0's in the $\gamma\gamma \to 3\pi^+3\pi^-$ reaction is limited by C-conservation to a maximum of 2 per event. The study of the ρ^0 content in this six pion final state is subject to a large combinatorial background. The $3\pi^+3\pi^-$ final state gives rise to 9 entries in all $\pi^+\pi^-$ distributions thereby making difficult the detection of the ρ^0 signal in our study. Our task is thus to detect a signal of at most two ρ^0's in the presence of at least seven background $\pi^+\pi^-$ pairs.

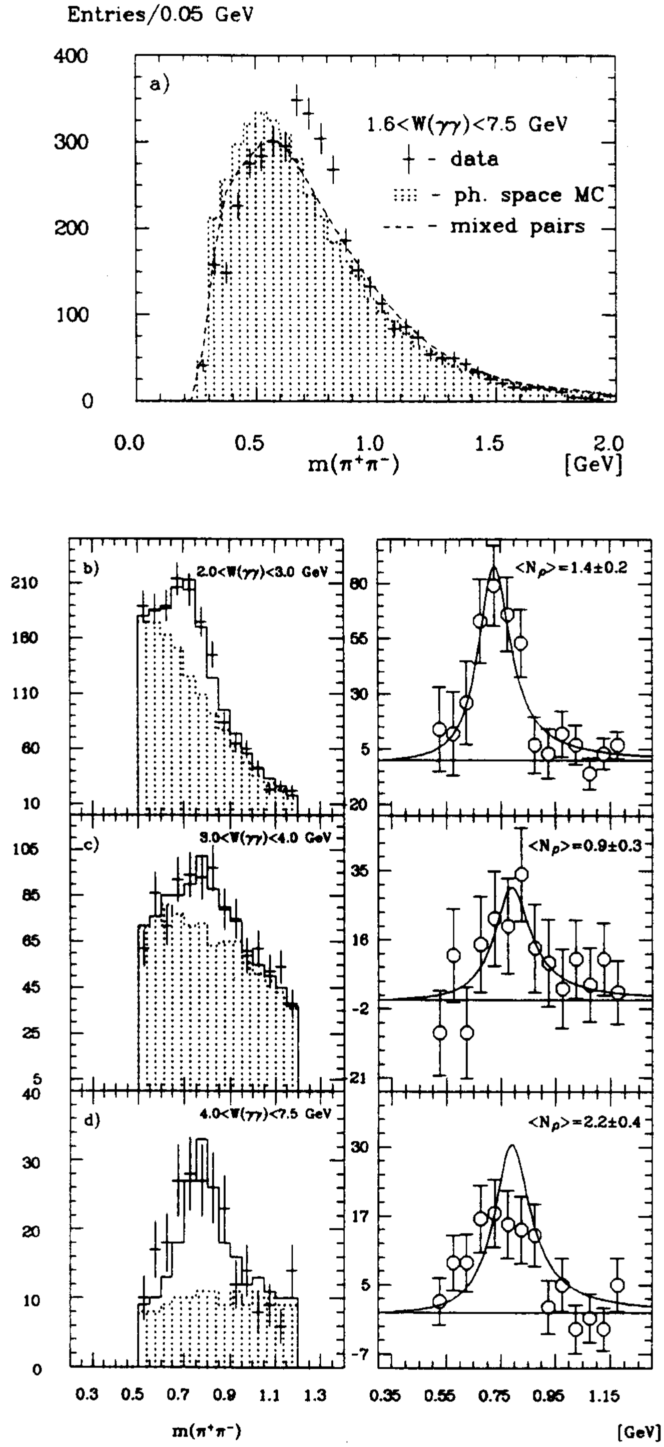

Fig. 1. a The $m(\pi^+\pi^-)$ distribution with 9 entries per event, data (crosses) phase space (dots), background from mixed event sample (broken line). **b–d** fit results are overlaid on the data as a full line histogram on the fitted $m(\pi^+\pi^-)$ (left) and as a full line on the background subtracted signal (right)

The average number of ρ^0 mesons per event, $\tilde{N}^{\rho^0}$, was determined by fitting the $m(\pi^+\pi^-)$ histogram to a ρ^0 Breit-Wigner ($\mathscr{BW}_\rho$) function plus a six pion non-resonant background ($\mathscr{BG}_{\pi\pi}$). The fit was carried out separately in three $W_{\gamma\gamma}$ intervals 2.0–3.0, 3.0–4.0 and

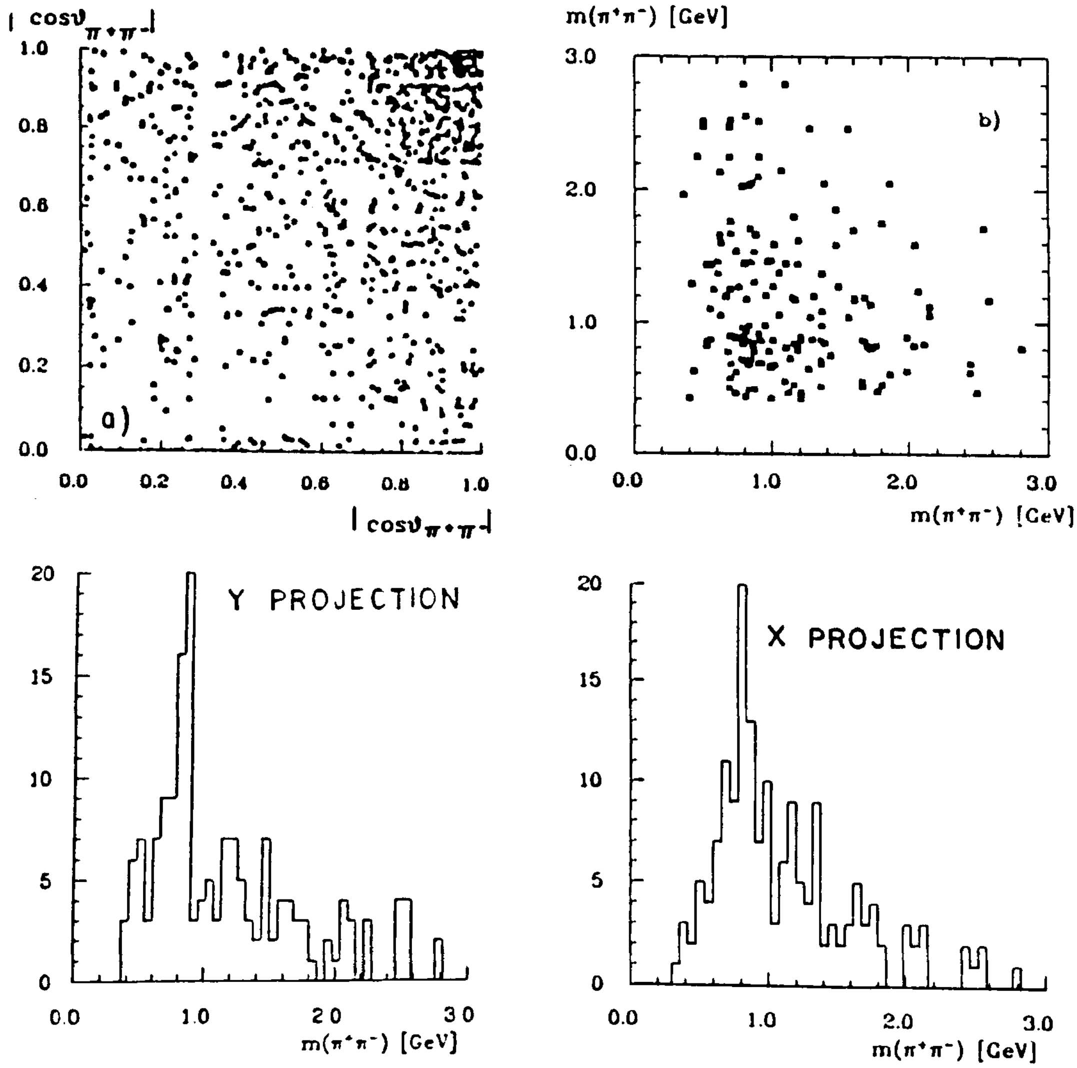

Fig. 2. a A correlation plot of $|\cos\vartheta_{\pi^+\pi^-}|$ in the $\gamma\gamma$ system of all $\pi^+\pi^-$ pairs (18 entries per event) in the $W_{\gamma\gamma}$ interval 4.0–7.5 GeV. **b** the $m(\pi^+\pi^-)$ correlation plot of pion pairs whose production angle in the $\gamma\gamma$ system is found in the interval $0.8 \leq |\cos\vartheta_{\pi^+\pi^-}| \leq 1.0$ in this $W_{\gamma\gamma}$ bin and its two projections

4.0–7.5 GeV, comparing the data $m(\pi^+\pi^-)$ to the following expression:

$$N^{\text{events}} \cdot ((9-\tilde{N}^{\rho^0}) \cdot \mathcal{BG}_{\pi\pi} + \tilde{N}^{\rho^0} \cdot \mathcal{BW}_{\rho}).$$

The non-resonant background was calculated using three different methods. The first method used Monte Carlo generated phase space while the second method used the like-sign $\pi^\pm\pi^\pm$ data distribution from the data sample. We also used for the non-resonant background a sample of $\pi^+\pi^-$ pairs which were formed by taking each π of the pair from a different event. For this last method we paired the positive pions coming from an eventh with a given $W_{\gamma\gamma}$ with the negative pions of another event whose $W_{\gamma\gamma}$ value was the closest. The results of the fits using these three different backgrounds yielded comparable results.

Figure 1a shows the $m(\pi^+\pi^-)$ distribution with two different backgrounds, normalized to the data sample, superimposed. Despite the large combinatorial background a clear structure is seen around 0.75 GeV which we identify with the ρ^0 meson. In plots 1b–d are shown the $m(\pi^+\pi^-)$ distributions for the three $W_{\gamma\gamma}$ bins 2.0–3.0, 3.0–4.0 and 4.0–7.5 GeV along with the best fits. Also shown, for each $W_{\gamma\gamma}$ interval, is the background subtracted ρ^0 signal described by a Breit-Wigner $\mathcal{BW}_\rho$ function. No ρ^0 signal is seen in the $W_{\gamma\gamma}$ range below 2.0 GeV. These fits were carried out in the 0.5–1.2 GeV $m(\pi^+\pi^-)$ mass range which covers the ρ^0 resonance region. The fit results are summarized in Table 1 where we give the number of events found in each interval, the mean number of ρ^0's per event, $\tilde{N}^{\rho^0}$, and the χ^2 per degree of freedom of the fit.

The values of $\tilde{N}^{\rho^0}$ found by this method are consistent, within errors, with the limit of $\tilde{N}^{\rho^0}=2$ dictated by C-conservation.

We found that the angular distribution of the $\pi^+\pi^-$ pairs in the $\gamma\gamma$ system tends to peak at small angles in the highest $W_{\gamma\gamma}$ interval studied. This peripheral feature can be used to reduce the combinatorial background. In Fig. 2a we show the correlation plot of $|\cos\vartheta_{\pi^+\pi^-}|$ of pairs in $W_{\gamma\gamma}$ 4.0–7.5 GeV, that do not share a common pion. The plot consists of 18 entries per event which show an enhancement in the angular interval $0.8 \leq |\cos\vartheta_{\pi^+\pi^-}| \leq 1.0$. Figure 2b shows the $m(\pi^+\pi^-)$ vs. $m(\pi^+\pi^-)$ scatter plot of pairs that are found in this angular interval. This figure has an average of about 3 entries per event which are bunched in the overlapping ρ^0 zone and its two projections reveal clear ρ^0 signals. The $\tilde{N}^{\rho^0} \approx 2.0$ yield in this $W_{\gamma\gamma}$ interval indicates the presence of a peripheral production mechanism of the ρ^0 vector mesons.

The observed ρ^0's can stem from several processes. Direct production in the reactions: $\gamma\gamma \to \rho^0\rho^0\pi^+\pi^-$ or $\gamma\gamma \to \rho^0 2\pi^+ 2\pi^-$ where the four pion system may be in the $J^P = 1^-$ state. Indirect production through the VDM channel $\gamma\gamma \to \rho^0\rho^0(1700)$ where the $\rho^0(1700)$ dominantly decays to a ρ^0 and two pions [9] or from the decay of other high mass mesons which are produced in $\gamma\gamma$ collisions.

In the search for the final state $\rho^0\rho^0(1700)$ we have utilized the fact that the $\rho^0(1700)$ decays mainly into $\rho\pi\pi$. The strategy was then to study events with a pair of ρ^0's and to search for the $\gamma\gamma \to \rho^0\rho(1700) \to \rho^0\rho^0\pi^+\pi^-$ channel. The $m(2\pi^+2\pi^-)$ mass recoiling against a ρ^0 shows no evidence for a resonance structure; moreover, this distribution is consistent with the similar distributions coming from the $\rho^0 2\pi^+ 2\pi^-$ and the $\rho^0\rho^0\pi^+\pi^-$ Monte Carlo. Nonetheless, upper limits for the process $\gamma\gamma \to \rho^0\rho^0(1700) \to \rho^0\rho^0\pi^+\pi^-$ can be calculated by a determination of the number of events with a ρ^0 pair, based on the large branching ratio of the $\rho^0(1700)$ decay through a $\rho^0\pi^+\pi^-$.

To determine the fractional contribution of the 3 possible states: $\rho^0\rho^0\pi^+\pi^-$, $\rho^0 2\pi^+ 2\pi^-$ and $3\pi^+ 3\pi^-$, we have carried out an extended maximum likelihood (EML) fit of the 6 pion final state. The EML routine, which is analogous to that used by the TASSO Collaboration [12], maximizes the following function:

$$\log \Lambda = \sum_{i=1}^{N} \left(\log \left[\sum_{j=1}^{3} \lambda_j \, g_j(\omega) / \int d\sigma_j(\omega) \, A_j(\omega) \right] - \sum_{j=1}^{3} \lambda_j \right) \tag{1}$$

where the sum is over the N events found in a given $W_{\gamma\gamma}$ bin. The fit parameters, λ_j, are the normalized fractional contributions of the 3 channels, $g_j(\omega)$ are the matrix elements for each production mechanism and $A_j(\omega)$ is the acceptance. Both g and A are functions of ω, which stands for all the two pion mass combinations. The integrals over $A(\omega)$ were obtained by smoothing fine binned $W_{\gamma\gamma}$ histograms of the various channels-j, generated with a full Monte Carlo simulation that included all detector effects. The fit is carried out in much larger bins than the bins used for these integrals.

In case of an isotropic ρ^0 production and an uncorrelated decay of the ρ^0's, the matrix elements for the $\rho 4\pi$ and the $\rho\rho\pi\pi$ processes contain only the ρ^0 Breit-Wigner function:

$$g_\rho = \left| \sum_{i=1}^{9} BW(\omega_i) \right|^2 \tag{2}$$

for a single ρ^0 state, and

$$g_{\rho\rho} = \left| \sum_{i=1}^{9} \sum_{j>i}^{9} BW(\omega_i) \, BW(\omega_j) \right|^2 \tag{3}$$

for a state with a pair of ρ^0's. The Breit-Wigner amplitue $BW(\omega_i)$ is given by [10]:

$$BW(\omega_i) = \frac{\sqrt{\omega_i \, \Gamma(\omega_i) \, m_\rho / q_i}}{\pi (m_{\rho^0}^2 - \omega_i^2 - \imath m_\rho \, \Gamma(\omega_i))}. \tag{4}$$

In order to include the peripheral features of the $\pi^+\pi^-$ pairs in the $W_{\gamma\gamma}$ 4.0–7.5 GeV interval, we multiplied each of the Breit-Wigner amplitudes in this $W_{\gamma\gamma}$ bin with the term, $e^{-p_T^2(\pi^+\pi^-)}$, where $p_T^2(\pi^+\pi^-)$ is the transverse momentum of the relevant pair with respect to the beam direction. This term improves significantly the goodness of the fit.

Since one cannot attribute a specific $\pi^+\pi^-$ pair to a ρ^0 decay, the matrix elements in (2) and (3) sum over all possible dipion mass combinations of the $3\pi^+3\pi^-$ final state. It can be shown that a coherent addition of the amplitudes in (2) and (3), denoted here as the CA model, cannot lead to distructive interferences. In fact adding up the matrix element amplitudes coherently, introduces constructive interference which enhances the apparent number of ρ^0's relative to the number of ρ^0 poles inserted in the amplitude [8]. Monte Carlo studies of the CA model showed observed ρ yields of $\tilde{N}^{\rho^0} = 1.5$ for the $\rho^0 2\pi^+ 2\pi^-$ and $\tilde{N}^{\rho^0} = 2.5$ for the $\rho^0\rho^0\pi^+\pi^-$ simulated states. An apparent yield of $\tilde{N}^{\rho^0} = 2.5$ does not signify a real violation of C-conservation (the input of ρ poles in the amplitude is exactly two) and is found to agree within errors with the observed $\tilde{N}^{\rho^0}$ in the data at $W_{\gamma\gamma} > 4.0$ GeV. Leaving out the interference terms in the matrix elements (denoted here as NCA model) reproduces the number of poles inserted in the amplitude. The average ρ^0 yield in the NCA model was $\tilde{N}^{\rho^0} = 1$ for the $\rho^0 2\pi^+ 2\pi^-$ and $\tilde{N}^{\rho^0} = 2$ for the $\rho^0\rho^0\pi^+\pi^-$ Monte Carlo states. The average ρ^0 Monte-Carlo yield was calculated for the whole 2.0–7.5 GeV $W_{\gamma\gamma}$ interval using the same method that was used for the data, and was found to be almost independent of $W_{\gamma\gamma}$.

Because of the constructive nature of the interferences, the CA average yield can be interpreted as an upper bound for the number of ρ^0's per event. Note however that extra dynamics like phase shifts between the pions and the rhos are not included in (2) and (3). In principle such phases could have averaged the interferences in the CA model to zero lowering $\tilde{N}^{\rho^0}$ to that of the NCA model [8]. The NCA and CA models are thus interpreted here as bounds (NCA lower bound and CA an upper bound) for the actual average ρ yield in the $\rho^0 2\pi^+ 2\pi^-$ and the $\rho^0\rho^0\pi^+\pi^-$ states. The data was fitted using either the CA or the NCA matrix elements without mixing between the two sets.

The fit parameters λ_i meet the following relations:

$$\lambda_{6\pi} + \lambda_{\rho 4\pi} + \lambda_{\rho\rho\pi\pi} = 1 \tag{5}$$

$$r_1 \cdot \lambda_{\rho 4\pi} + r_2 \cdot \lambda_{\rho\rho\pi\pi} = \tilde{N}^{\rho^0} \tag{6}$$

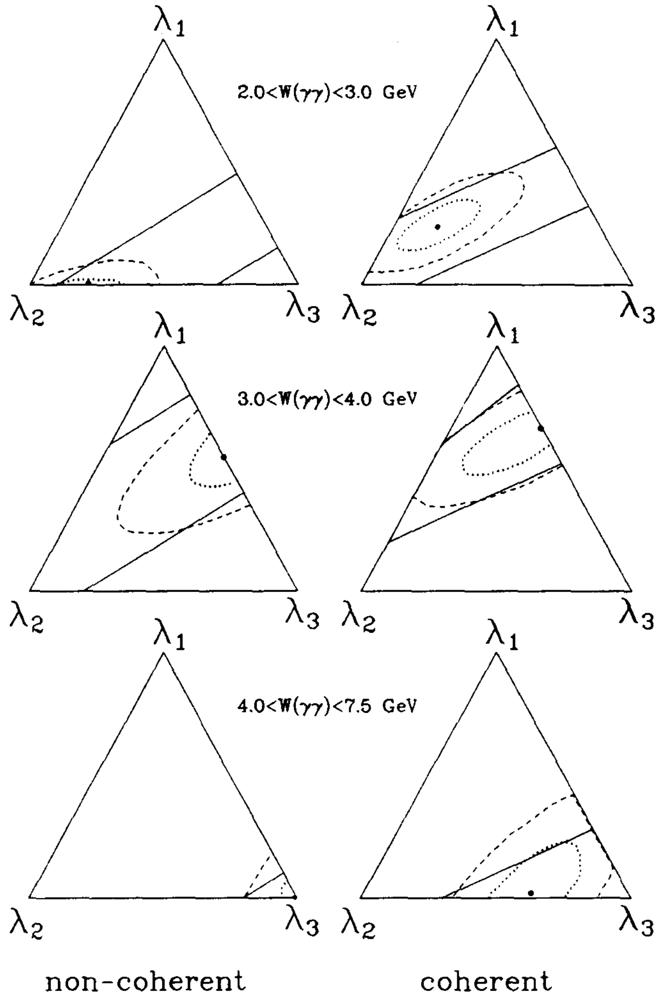

Fig. 3. The EML fit results are plotted on the triangle defined by (5); the most likely result is marked with a bold point, dotted line is the 1σ contour, broken line is the 2σ contour and full lines are the solution of (6). λ_1, λ_2, λ_3 are the fractions $\gamma\gamma \to 3\pi^+3\pi^-$, $\gamma\gamma \to \rho^0 2\pi^+2\pi^-$ and $\gamma\gamma \to \rho^0\rho^0\pi^+\pi^-$ respectively

Table 2. Cross sections for the processes: $\gamma\gamma \to 3\pi^+3\pi^-$, $\gamma\gamma \to \rho^0 2\pi^+2\pi^-$ and $\gamma\gamma \to \rho^0\rho^0\pi^+\pi^-$

$W_{\gamma\gamma}$ [GeV]	$3\pi^+3\pi^-$ [nb]	$\rho^0 4\pi$ [nb]	$\rho^0\rho^0\pi\pi$ [nb]	Channel cross section [nb]	MC Model
2.0–3.0	2.3±1.0	4.8±1.6	1.2±0.9	8.3±0.5	CA
2.0–3.0	0.0±0.5	7.1±1.3	1.7±1.3	8.8±0.6	NCA
3.0–4.0	3.7±0.9	0.7±1.4	1.5±0.9	5.9±0.5	CA
3.0–4.0	3.3±0.5	0.0±2.5	2.6±0.6	5.9±0.5	NCA
4.0–7.5	0.0±0.2	0.3±0.2	0.5±0.1	0.8±0.1	CA
4.0–7.5	0.0±0.1	0.0±0.1	1.1±0.1	1.1±0.1	NCA

where r_1, r_2 are the mean number of ρ per event expected from the NCA and the CA models i.e. $r_1 = 1$, (1.5) and $r_2 = 2$, (2.5) respectively, and $\tilde{N}^{\rho^0}$ as determined from the fit of the $m(\pi^+\pi^-)$ distribution with the former method. Equation (5) defines an equilateral triangle, with the parameters λ_i as the normals to the sides of this triangle.

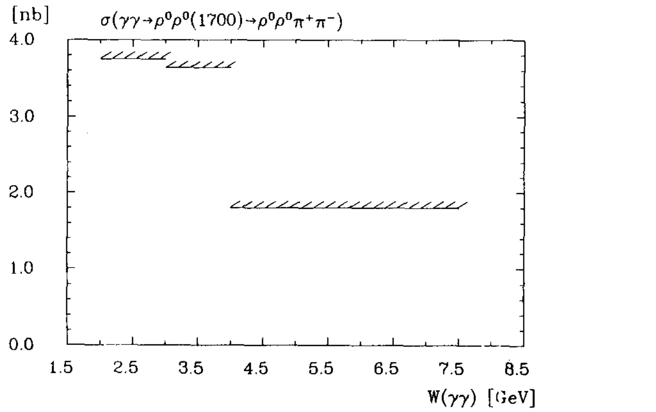

Fig. 4. Upper limit for the reaction $\gamma\gamma \to \rho^0\rho^0(1700) \to \rho^0\rho^0\pi^+\pi^-$. Background from other channels that decay via a ρ^0 was not subtracted

The solution of (6) are two lines (denoted here as a bound), one for $\tilde{N}^{\rho^0} + \Delta\tilde{N}^{\rho^0}$ and the other for $\tilde{N}^{\rho^0} - \Delta\tilde{N}^{\rho^0}$ as determined in each $W_{\gamma\gamma}$ bin with the former method. In Fig. 3 we plot the resulting λ_i from the EML fit on the triangle defined in (5), together with the bound of (6). Fit results that are one standard deviation (1σ) away from the most likely set of parameters (marked with a bold point), are found within the bound defined by (6) thereby showing agreement with $\tilde{N}^{\rho^0}$ as determined with the former method. Despite the large correlation between the various fractions λ_i we find a substantial contribution of the $\rho^0\rho^0\pi^+\pi^-$ channel in each of the $W_{\gamma\gamma}$ bins. The cross sections for these channels are given in Table 2 together with the topological cross section in each of the $W_{\gamma\gamma}$ bins as obtained by summing up the 3 contributions. Note that both models (CA and NCA) lead to consistent results within their errors. We estimate the systematical error for the cross sections to be about 13% [7].

The $\rho^0\rho^0\pi^+\pi^-$ contribution rises with $W_{\gamma\gamma}$ as following: from (15±11)% (using the CA model) to (19±15)% (NCA) of the topological cross section in $W_{\gamma\gamma}$ between 2.0 to 3.0 GeV, (25±15)% to (44±10)% in the interval 3.0–4.0 GeV and (63±13)% to (100±9)% for 4.0–7.5 GeV.

Using the NCA results for the $\rho^0\rho^0\pi^+\pi^-$, we derive upper limits for the $\rho^0\rho^0(1700)$ pair production process. The 95% c.l. upper limits (1.92 standard deviation from the most likely $\lambda_{\rho\rho 2\pi}$ parameter) are shown in Fig. 4. Based on its large branching ratio to the $\rho\pi\pi$ decay mode, this upper limit is independent of the $\rho^0(1700)$ parameters such as its width, interference between two resonances [11] etc. We note the fact that background from other possible processes that could yield a ρ^0 pair was not subtracted.

In summary we have analysed the ρ^0 content of the reaction $\gamma\gamma \to 3\pi^+3\pi^-$ in the $W_{\gamma\gamma}$ range between 1.6–7.5 GeV. Below 2.0 GeV we did not observe a ρ^0 signal. The results show an average of more than one ρ^0 per event in the final state, but not more than two ρ^0's per event (within the errors), which is in agreement with charge conjugation conservation. In particular an average yield of about $2\rho^0$'s per event is seen in the $4.0 < W_{\gamma\gamma} < 7.5$ GeV $W_{\gamma\gamma}$ mass region whose angular distribution indicates a peripheral ρ^0 production mechanism. Using an EML fit routine we have determined the cross sections for the following processes: nonresonant $\gamma\gamma \to 3\pi^+ 3\pi^-$, $\gamma\gamma \to \rho^0 2\pi^+ 2\pi^-$ and $\gamma\gamma \to \rho^0 \rho^0 \pi^+ \pi^-$. The cross section of the last process was used to derive an upper limit to the reaction $\gamma\gamma \to \rho^0 \rho^0(1700) \to \rho^0 \rho^0 \pi^+ \pi^- \to 3\pi^+ 3\pi^-$ which is independent of the $\rho^0(1700)$ parameters.

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