Z. Phys. C - Particles and Fields 23, 223-232 (1984)

Zeitschrift für Physik C Particles and Fields

Production of the $f_0(1270)$ Meson in Photon-Photon Collisions

CELLO-Collaboration

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Received 27 February 1984

Abstract. The production of the f_0 in two photon collisions, with the subsequent decay $f_0 \to \pi^+\pi^-$ has been observed in the CELLO detector at PETRA. The f_0 peak was found to lie on a dipion continuum and to be shifted downwards in mass by $\simeq 50$ MeV/c^2. The $\pi\pi$ mass spectrum from 0.8 to 1.5 GeV/c^2 was well fitted by the model of Mennessier using only a unitarised Born amplitude and helicity $2 f_0$ amplitude. The previously observed mass shift and distortion of the f_0 peak are explained by strong interference between the Born and f_0 amplitudes. The only free parameter in the fit of the data to the model is the radiative width $\Gamma_{\gamma\gamma}(f_0)$. It was found that:

$$\Gamma_{\gamma\gamma}(f_0) = 2.5 \pm 0.1 \pm 0.5 \text{ keV}$$

where the first (second) quoted errors are statistical (systematic).

1. Introduction

Within the last few years there have been many measurements at e^+e^- storage rings of the exclusive production of resonant states in virtual photon-photon collisions. The essential physical parameter determined in such experiments, the radiative width $\Gamma_{\gamma\gamma}$, has been the subject of a large number of

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theoretical predictions over the last decade or so [1].

Measurements have recently been made of the production of η' [2–4], A_2 [5, 4], f' [6] and η [7]. Several previous studies [8–10], have been made of the process considered in this paper:

$$e^+ e^- \to f_0 e^+ e^- \\ \quad \hookrightarrow \pi^+ \pi^-$$

while one experiment, [5], has observed the $\pi^0 \pi^0$ decay mode of the f_0. In all of these experiments the scattered electron and positron are unobserved. The exclusive final state resulting from the decay of the resonance was separated from background by kinematical cuts. A common feature of the previous analyses of f_0 production was the difficulty of explaining the shape of the dipion mass spectrum in the region of the f_0 peak in terms of the previously measured [11] mass and width of the f_0.

Mass shifts of $\simeq 40$ MeV/c^2 were reported for both the charged and neutral dipion decay modes [12]. The shift and distortion of the f_0 peak were variously interpreted in terms of additional resonant contributions [10] or as an interference effect between the Born and f_0 amplitudes [9]. In [9] the dipion mass spectrum was fitted to a simple 3 parameter model taking into account the Born term and the f_0 Breit-Wigner amplitude. No partial wave analysis of the amplitudes was performed. We report here an analysis based on a model [13] in which the $I=0$, S and D partial waves are calculated taking into account the dipion Born term and a pure helicity $2 f_0$ amplitude. Unitarity corrections are also included but are found to be small. Resonant contributions other than the f_0 are not included in the model at this stage. A later publication will extend the present analysis to the low mass region $0.4 < M_{\pi\pi} < 1.0$ GeV/c^2 where an excess of events relative to the Born contribution has been reported [14] by an experiment at DCI. Upper limits for the radiative widths of possible scalar resonances in the f_0 mass region will be given in the same publication.

2. Event Selection and Background Rejection

The present analysis is based on an integrated luminosity of 11.4 pb^{-1} collected by the CELLO detector at PETRA in 1980–81. A description of the detector can be found in [15].

The fast trigger [16] required at least two tracks in the central detector in the $R\phi$ projection (the plane perpendicular to the colliding beams) with transverse momentum greater than 200 MeV/c and in addition at least one track in RZ projection (i.e. in a plane containing the beams) originating from within ± 10 cm of the interaction point. The angular constraint in the $R\phi$ trigger accepted only events separated in azimuth by at least 6°. The RZ trigger was very effective in rejecting beam gas background and made possible the minimum bias 2 track requirement. The angular acceptance of the charged trigger was $|\cos\theta| < 0.87$. The track requirement of the trigger was verified by an on-line program with an improved spatial resolution in the $R\phi$ projection. Before passing events to the full track reconstruction programmes a preliminary selection of candidate events for low multiplicity two photon production was made. This selection was made on the basis of track candidates ("masks") recorded by the fast charged trigger. Events with a large track multiplicity (>4) were rejected and it was required that all charged particle tracks have a relative angular separation in $R\phi$ projection of at least 200 mrad. In addition all events with an excessivly large number of hits in the central tracking chamber were rejected. This last cut was necessary to remove background triggers generated by off momentum particles. An independant study of two charged particle events identified by tagging one of the scattered electrons indicated that 6% of good events were removed by this cut. The overall efficiency of the pre-selection procedure was found to be 87 ± 6%.

As the candidate events were found to be clean, with well separated tracks, loose track finding criteria could be used (only ≥ 4 out of the 12 track chambers required). The track reconstruction efficiency was estimated to be $\simeq 99$% for tracks satisfying the $R\phi$ trigger requirement. To select events corresponding to the exclusive production of two charged particles in 2γ interactions the following cuts were made: (the Z axis is parallel to the colliding beams).

(i) Two charged particles of opposite sign
(ii) $|Z_0| < 2.5$ cm ($Z_0 \equiv Z$ co-ordinate of track intersection with the beam axis)
(iii) $|\cos\theta| < 0.85$ ($\theta \equiv$ polar angle of the track relative to beams)
(iv) $p_T > 0.35$ GeV/c ($p_T \equiv$ track momentum transverse to the beam axis)
(v) $\cos\theta_{RZ}^{\text{acoll.}} < 0.995$ ($\theta_{RZ}^{\text{acoll.}} \equiv$ acollinearity angle between the tracks in RZ projection)
(vi) $\Sigma p_T < 0.1$ GeV/c
(vii) $E_{\text{visible}} < 20$ GeV.

After the cuts (ii) and (v) the residual background (beam gas and cosmic muons) is found to be $\simeq 1$%. The cut (v) is required to remove cosmic muons. The cuts (iii) and (iv) ensured that the accepted events were not too near to the edges of the trigger acceptance in angle and track transverse momentum respectively. Exclusive 2 particle events were selected by the cut (vi).

The residual background from inclusive events:

$$e^+ e^- \to \pi^+ \pi^- + \ldots + e^+ e^-$$

was estimated to be 2%, by comparing the Σp_T distribution in the mass range $1.0 < M_{\pi\pi} < 1.4\ \mathrm{GeV/c^2}$ for 2 particle events selected with the above cuts, with that given by 3 charged particle events where one track is discarded to give a charge balanced pair.

3. Acceptance Corrections and Subtraction of QED Background

The QED reactions $e^+ e^- \to l^+ l^- e^+ e^-$ are simulated by a Monte Carlo generator using the exact cross section for transverse photons [17, 18], including the dependence on the virtual photon masses [19] in the cross section for:

$$\gamma^* \gamma^* \to \begin{matrix} ee \\ \mu\mu. \end{matrix}$$

Interference effects between produced and scattered electrons, radiative corrections [20] and contributions from inelastic Compton scattering graphs [21] are neglected. The generator has been compared in detail with the exact Feynman diagram calculation of Vermaseren [22, 23]. For untagged reactions the total cross sections and various differential cross sections showed good agreement at the few percent level.

The dipion mass spectrum was found by subtracting from the observed mass distribution the absolutely normalised sum of the $\mu\mu$ and ee Monte Carlo mass distributions (see Fig. 1). All particles were assigned the pion mass. The QED mass distributions are given by the generator described above and include a full simulation of the CELLO detector. As can be seen from Fig. 1, there is no evidence for an excess of events over the QED prediction for masses $> 1.5\ \mathrm{GeV/c^2}$.

This is consistent with the following considerations:

(i) Agreement for the absolute normalisation:

$$\frac{N^{\mathrm{evts.}}(M > 1.5\ \mathrm{GeV/c^2})}{N^{ee+\mu\mu}_{\mathrm{pred.}}(M_{\pi\pi} > 1.5\ \mathrm{GeV/c^2})} = 0.95 \pm 0.09.$$

(ii) The measurement of the PLUTO Collaboration [24]

$$\frac{N^{h^+h^-}}{N^{ee+\mu\mu}} \leqq 0.06 \quad \text{at } 90\%\ \text{C.L.}\ (h = \pi, K, p)$$

$$M_{\pi\pi} > 2.0\ \mathrm{GeV/c^2}.$$

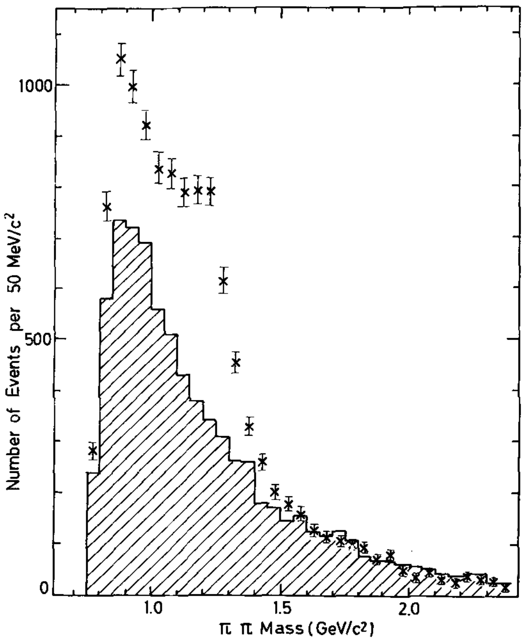


Fig. 1. Points with error bars: invariant mass of the two observed tracks (π mass assumed). Shaded histogram: absolutely normalised QED ($2\mu + 2e$) Monte Carlo distribution

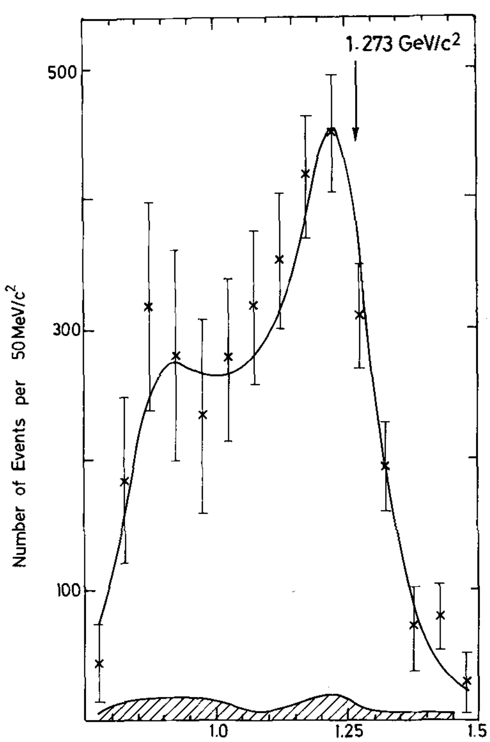
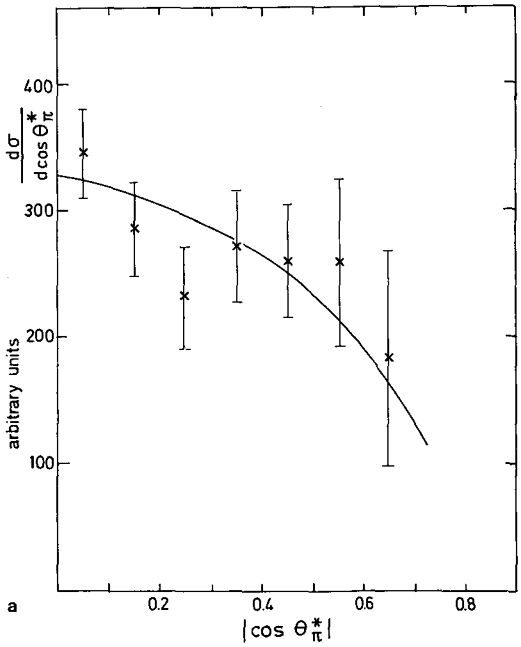
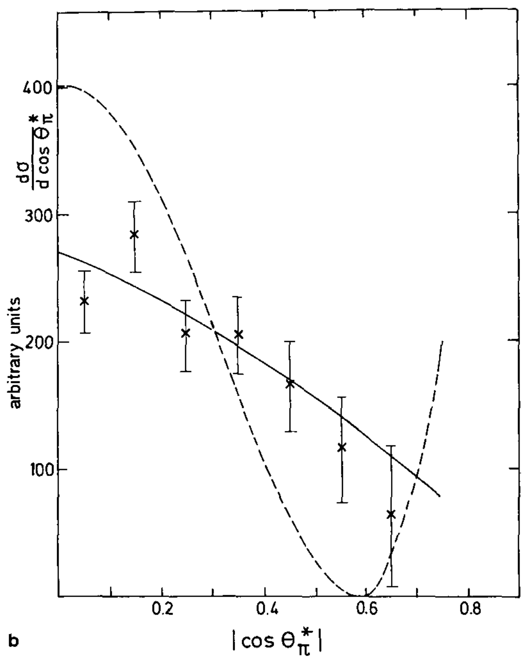


Fig. 2. QED subtracted invariant mass distribution. Solid line: Prediction of Mennessier for the $\pi\pi$ contribution (with $\Gamma_{\gamma\gamma}(f_0) = 2.5\ \mathrm{keV}) + K^+K^-$ estimate from [6]. The K^+K^- contribution is shaded



a



b

Fig. 3a and b. QED subtracted acceptance corrected angular distributions in $\pi\pi$ rest frame. The solid curves are the Mennessier prediction (pure $\lambda=2$ coupling for the f_0). **a** $1.0<M_{\pi\pi}<1.2$ GeV/c^2 (lower half of f_0 peak), **b** $1.2<M_{\pi\pi}<1.4$ GeV/c^2 (upper half of f_0 peak). The dashed curve in **b** is the relatively normalised prediction for pure $\lambda=0$ coupling

(iii) The good agreement of the angular distribution for masses above 1.4 GeV/c^2 (see Fig. 4) with the expectation from the purely QED processes.

Comparing the observed mass distribution with the QED expectation for masses below 1.5 GeV/c^2 (Fig. 1, cross hatched histogram) it can be seen that there is a large excess of events both in the f_0 mass region and below. Subtracting the expected QED contribution gives the distribution shown in Fig. 2. The error bars shown in Fig. 2 include the quadratic sum of both the point by point statistical errors on the data and the Monte Carlo and the overall systematic error ($\pm 8.4\%$) in the absolute QED normalisation. The normalisation error has the following contributions

- luminosity measurement (wide angle bhabha scattering) $\pm 5\%$
- Trigger efficiency (78%) $\pm 3\%$
- Event selection efficiency (87%) $\pm 6\%$

The $\pi\pi$ continuum below the f_0 is substantial and the peak is shifted downwards in mass by roughly 50 MeV/c^2. We verified that this shift is not instrumental by observing η' production [4]. The measured mass in the decay channel $\eta' \to \rho^0 \gamma \to \pi^+ \pi^- \gamma$ of 957 ± 3 MeV/c^2 agrees with the PDG value [11]. In the subsequent analysis this subtracted distribution is corrected for the measured K^+K^- contribution [6]. Figures 3a, b show the folded, QED subtracted, and acceptance corrected centre of mass angular distributions $\frac{d\sigma}{d\cos\theta_\pi^*}$ for the lower and upper halves of the f_0 peak respectively. θ_π^* is the angle of one of the final state pions relative to the virtual photon direction in the $\gamma\gamma$ centre of mass system. As the virtual photon direction is unknown it is approximated by the initial e^+e^- direction. The acceptance correction as a function of θ_π^* is done using an analytical formula based on the equivalent photon approximation. If θ_c is the minimum lab angle defined by the acceptance cut for charged particles (32°), the detection efficiency for a given centre of mass angle θ^* is [18]:

$$\varepsilon(\cos\theta^*) = \frac{\ln\frac{1}{\alpha} - z\left(\frac{1}{\alpha} - \alpha\right)}{\ln\frac{1}{z} - \frac{3}{4}} \tag{1}$$

where $\alpha \equiv \frac{1-\beta_{\mathrm{MAX}}}{1+\beta_{\mathrm{MAX}}}$ $\qquad z^2 \equiv \left(\frac{m_{\pi\pi}}{2E}\right)^2 \ll 1$

and

$$\beta_{\mathrm{MAX}} = \frac{\cos\theta^* \{\sqrt{R[1+(R-1)\cos^2\theta^*]} - 1\}}{1 + R\cos^2\theta^*}$$

$$R \equiv \tan^2\theta^* / \tan^2\theta_c.$$

The validity of the approximate formula (1) is checked by comparing the acceptance corrected un-

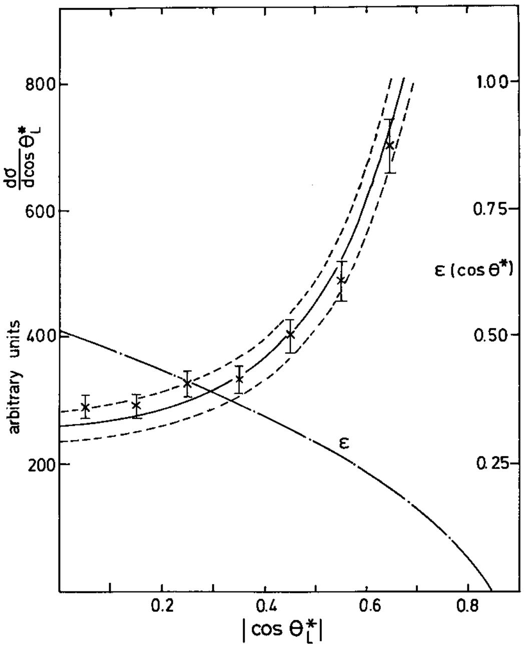


Fig. 4. Unsubtracted acceptance corrected distribution for $M_{\pi\pi} > 1.4$ GeV/c^2. The solid line is the absolutely normalised QED $(2e+2\mu)$ prediction. The dashed-dotted line indicates the acceptance (calculated using (1)) as a function of $\cos\theta^*$. The dashed lines are the $\pm 1\sigma$ limits of the absolute normalisation error

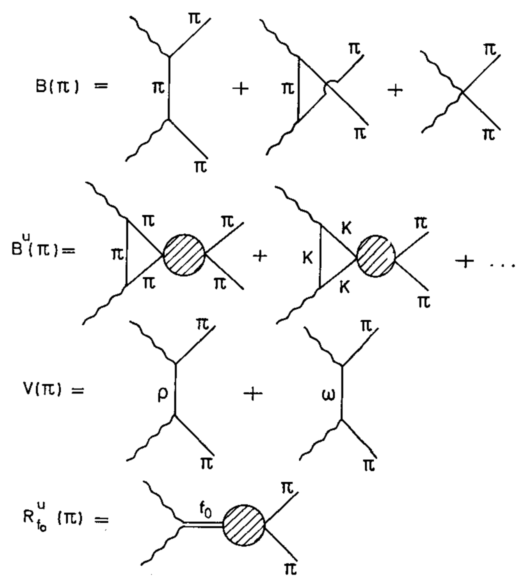


Fig. 5. Diagrams contributing to the amplitudes in the Mennessier model. $B(\pi)$: Pure Born term, $B^u(\pi)$: Unitarity corrections to Born term, $V(\pi)$: Vector exchange term, $R^u_{f_0}(\pi)$: f_0 amplitude with unitarity corrections

subtracted angular distribution in the high mass region: $M_{\pi\pi} > 1.4$ GeV/c^2 (Fig. 4) with the QED expectation, valid for low q^2 virtual photons:

$$\frac{d\sigma}{d\cos\theta^*} = \frac{2\pi\alpha^2}{M_{ll}^2}\,\frac{(1+\cos^2\theta^*)}{(1-\cos^2\theta^*)}. \tag{2}$$

The agreement of the acceptance corrected curve with the QED prediction can be seen to be quite satisfactory. The dotted lines in Fig. 4 indicate the $\pm 1\sigma$ limits of the absolute normalisation error. The detection efficiency function equation (1) corresponding to our cuts is also shown in Fig. 4. To reduce statistical fluctuations due to limited Monte Carlo statistics the QED angular distribution subtracted in the f_0 region was analytically calculated as the product of (1) and (2). The fully simulated Monte Carlo was used however to determine the overall normalisation. The errors shown in Figs. 3a, b include the quadratic sum of the point by point statistical errors on the data, as well as the overall systematic error from the normalisation uncertainty.

4. Comparison with the Model of Mennessier

We have compared the $\pi\pi$ mass spectrum and angular distribution with the model of Mennessier [13]. This model, which makes rather weak theoretical assumptions describes the production of $\pi\pi$ and KK pairs by real photons in the region of 2γ mass below 1.4 GeV/c^2 using a unitary and analytic coupled channel K matrix formalism.

The amplitude for the process $\gamma\gamma \to \pi\pi$ or $\gamma\gamma \to KK$ for a given charge state, total angular momentum, and total isotopic spin is written in the form:

$$T^u = B^u + V^u + \sum_i R_i^u \tag{3}$$

where e.g. $B^u = B^0 + B_c^u$.

B^0 is the pure Born term, B_c^u is the correction to B^0 due to unitarisation (final state scattering effects) and similarly for the vector exchange (V) and directly coupled resonance (R_i) amplitudes.

Diagrams illustrating the meaning of these terms for the $\gamma\gamma \to \pi\pi$ case are shown in Fig. 5. Only $I=0$, S and D waves are considered. The unitarisation corrections (final state rescattering effects) are represented by shaded bubbles. These are completely determined by purely strong interaction parameters ($\pi\pi$ and KK phase shifts and inelasticities). In [13] the experimental strong interaction data were fitted to an analytic unitary K matrix. These fits yielded three different sets of parameters A, B, C. A is valid only in the low mass region < 0.9 GeV/c^2. B and C

are similar, except that B has a narrow S^* resonance, which is missing in solution C. In the f_0 mass region B and C show similar behaviour, and as the unitarity corrections are not large, we have chosen the solution C. The strong interference effects between the f_0 amplitude and the Born term, to be discussed below, are independent of the details of the unitarisation corrections. Within our experimental errors the "pure Born" and unitarised Born amplitude give equivalent results.

In fact a satisfactory fit to our data (mass distribution and angular distributions) is found by retaining only the unitarised Born term and a helicity $2 f_0$ amplitude. The absence of a significant helicity 0 contribution is consistent both with our angular distributions (see Fig. 3b) and with a previous measurement of $\gamma\gamma \to f_0 \to \pi^0 \pi^0$ [5].

Upper limits on the helicity 0 contribution will be given in a future publication (see Sect. 1). This suppression of the helicity 0 contribution for almost real photons is expected from general theoretical arguments [25–27]. Since the pure Born terms can be exactly calculated and the unitarisation corrections are determined from purely strong interaction data, the only free parameter fitted to our data is $\Gamma_{\gamma\gamma}(f_0)$ which describes the "direct" $\gamma\gamma f_0$ coupling. This does not correspond exactly with the observed f_0 signal since the helicity 2 projection of the Born term may give a small contribution to the f_0 signal by final state scattering effects. Because of strong interference effects between the f_0 and Born amplitudes it is not possible to give a simple parametrisation of the difference between the "direct" and total f_0 contributions. $\Gamma_{\gamma\gamma}(f_0)$ is the relevant parameter for comparison with theoretical predictions based on internal meson structure (e.g. the quark model), whereas in evaluating dispersion relations or sum rules (see Sect. 6) the full partial wave amplitudes measured by the fit to the experimental distributions should be used.

As the model of Mennessier is valid only for real photons it is necessary to convolute the calculated cross section with virtual photon flux functions before comparing to the measured distributions. As for the lepton pairs, this is done using the exact transverse luminosity function [17, 18].

Apart from allowing for the effect of a *VDM* type photon coupling to the f_0 (see below), the q^2 dependence of the $\gamma\gamma f_0$ coupling is ignored. In particular no allowance is made for possible changes in the helicity state of the f_0 as q^2 is varied. As large q^2 virtual photons are effectively removed by the rather stringent cut on $\sum p_T$ (cut (vi) above) no significant effects of this type are expected in any case.

The double differential cross section $\frac{d^2\sigma}{dM_{\pi\pi}\, d\cos\theta^*_\pi}$ calculated according to the formulae given in [13] is used as a weighting function in a Monte Carlo generator, that also chooses the energies and angles of the scattered electrons according to the distributions of [18]. The final value of $\Gamma_{\gamma\gamma}(f_0)$ was found by comparing the number of events observed in the mass region $1.0 < M_{\pi\pi} < 1.4\ \mathrm{GeV/c^2}$ with the predicted number of fully simulated Monte Carlo events in the same region. Because of interference and final state scattering effects (see below) the number of events is not strictly proportional to $\Gamma_{\gamma\gamma}(f_0)$. The relation between $\Gamma_{\gamma\gamma}$ and the expected number of events was found by interpolation between several Monte Carlo samples with different values of $\Gamma_{\gamma\gamma}$ near to the best fit value.

The curve shown in Fig. 2 is the result of this one parameter fit to the dipion mass spectrum. Also included in the curve is the estimated K^+K^- contribution (cross hatched). This was calculated directly from the mass distributions given in [6] using the acceptance function and the value of $\Gamma_{\gamma\gamma}(f')$ quoted in the same paper. The K^+K^- correction is seen to be small. The mass spectrum is well fitted by the model ($\chi^2 = 7.3$ for 14 D.F.) with a value for $\Gamma_{\gamma\gamma}(f_0)$ of 2.46 keV. More details on the calculation of the radiative width, including error analysis, are given in Sect. 5.

The model also gives a good fit to the angular distributions (Fig. 3a, b). The dashed curve in Fig. 3b shows the angular distribution for spin 2 helicity $0: (3\cos^2\theta^* - 1)^2$. Helicity 2 coupling for the f_0 with an angular distribution proportional to $\sin^4\theta^*$ (solid curves in Fig. 3a, b) is consistent with the data, while pure helicity 0 is excluded. The satisfactory fit to our dipion distribution shown in Figs. 2, 3 was obtained with all direct scalar resonance ($\sigma(700)$, S^*, $\varepsilon(1300)$) couplings set to zero. In particular we see no evidence for a narrow S^* structure [10] in our mass spectrum. Upper limits on $\Gamma_{\gamma\gamma}$ for scalar resonances will be given in a later publication.

The f_0 mass peak is well fitted using the world average [11] mass and width for the f_0. The shift of the observed f_0 peak to lower masses is demonstrated in Fig. 6. Curve A is the prediction of the model described above with $\Gamma_{\gamma\gamma}(f_0) = 3.0\ \mathrm{keV}$. Curve B has exactly the same parameters except the f_0 and Born amplitudes are now added incoherently. It can be seen that the shift and distortion of the f_0 peak are due to strong interference effects between the Born and f_0 amplitudes. The interference is constructive below the f_0 peak and destructive above. In fact, in the region above $1.5\ \mathrm{GeV/c^2}$, the Born term is almost completely suppressed by the interference with the high mass tail of the f_0 amplitude. This is con-

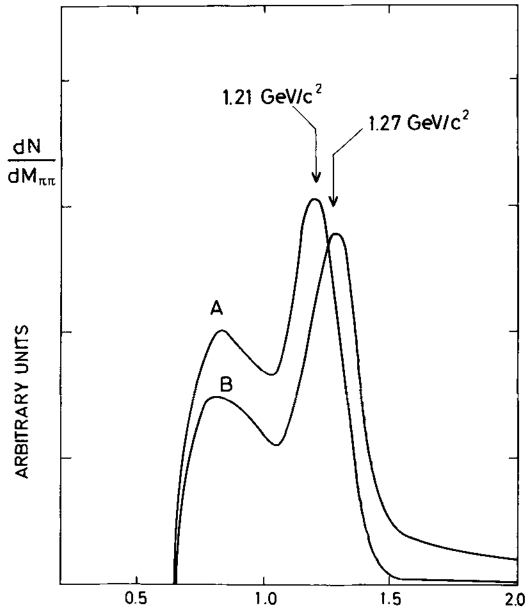


Fig. 6. Monte Carlo $\pi\pi$ mass distributions for $\Gamma_{\gamma\gamma}(f_0)=3.0$ KeV. Curve A: $|\mathrm{Born}+f_0|^2$, Curve B: $|\mathrm{Born}|^2+|f_0|^2$

sistent with the observations of [10] and [24], where it was found that the simple Born term grossly overestimates the level of dipion continuum for masses >1.5 GeV/c^2 [10] and 2.0 GeV/c^2 [24].

A downward shift of the f_0 peak is also predicted in a recent paper by Lyth [28]. Here interference of the f_0 with a pure Born amplitude is considered with particular emphasis on correct high energy behaviour of the amplitudes. The solution presented in [28] with a real f_0 coupling gives a mass shift in good agreement with our measurements. Another solution with an imaginary f_0 coupling gives too large a downward shift to fit our data.

Using the same parameters in the model as in the fit curves shown in Figs. 2, 3 the corresponding $\pi^0\pi^0$ mass distribution has been generated. In this case there is no direct Born term and the $\pi^0\pi^0$ continuum results purely from final state rescattering effects of the type $\pi^+\pi^-\to\pi^0\pi^0$. Visual comparison with the $\pi^0\pi^0$ spectrum measured by the Crystal Ball Collaboration [5] indicates satisfactory agreement for the level of this continuum. On fitting the simulated $\pi^0\pi^0$ distribution with a Breit-Wigner function a downward shift of 20 MeV/c^2 is found for the f_0 mass, to be compared with the measured value [5] of 35 ± 14 (stat)$\pm<24$(syst) MeV/c^2. Adding vector exchange contributions with couplings suggested in [13] produces too large a continuum on the high mass side of the f_0 in the $\pi^0\pi^0$ mass distribution to be consistent with the Crystal Ball measurement [5]. As shown above no such contributions are needed to fit the charged pion distributions.

5. Determination of $\Gamma_{\gamma\gamma}(f_0)$

From the Monte Carlo simulation of $\pi\pi$ events the functional relationship between $\Gamma_{\gamma\gamma}$ and the cross section within the experimental cuts (geometrical and kinematic) is determined:

$$\sigma_{\mathrm{cut}}^{\pi\pi}=f(\Gamma_{\gamma\gamma}). \tag{4}$$

As mentioned above f is not a strictly linear function of $\Gamma_{\gamma\gamma}$. $\sigma_{\mathrm{cut}}^{\pi\pi}$ is related to the total number of events observed within the cuts ($\pi\pi+\mu\mu+ee$), $N_{\mathrm{TOT}}=5430$, by the relation:

$$\sigma_{\mathrm{cut}}^{\pi\pi}=\frac{N_{\mathrm{TOT}}}{E_T\cdot E_{ps}\cdot\mathscr{L}}-\sigma_{\mathrm{cut}}^{\mathrm{QED}} \tag{5}$$

where $\sigma_{\mathrm{cut}}^{\mathrm{QED}}$ is the $ee+\mu\mu$ cross section corresponding to $\sigma_{\mathrm{cut}}^{\pi\pi}$, $\mathscr{L}$ is the total luminosity, E_T is the trigger efficiency, and E_{ps} is the pre-selection efficiency. $\Gamma_{\gamma\gamma}$ is found by solving (4) and (5):

$$\Gamma_{\gamma\gamma}=f^{-1}\left(\frac{N_{\mathrm{TOT}}}{\mathscr{L}'}-\sigma_{\mathrm{cut}}^{\mathrm{QED}}\right) \tag{6}$$

where $\mathscr{L}'=E_T\cdot E_{ps}\cdot\mathscr{L}$.

As the relation between $\sigma_{\mathrm{cut}}^{\pi\pi}$ and $\Gamma_{\gamma\gamma}$ is almost linear: $\Gamma_{\gamma\gamma}\simeq K\sigma_{\mathrm{cut}}^{\pi\pi}$ the fractional error on $\Gamma_{\gamma\gamma}$ is given by:

$$\frac{\delta\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}}=\frac{\delta K}{K}+\frac{\delta N_{\mathrm{TOT}}}{N_s}-\frac{N_{\mathrm{TOT}}}{N_s}\left(\frac{\delta\mathscr{L}'}{\mathscr{L}'}\right)-\frac{(N_{\mathrm{TOT}}-N_s)}{N_s}\,\frac{\delta\sigma_{\mathrm{cut}}^{\mathrm{QED}}}{\sigma_{\mathrm{cut}}^{\mathrm{QED}}} \tag{7}$$

where $N_s=\mathscr{L}'\,\sigma_{\mathrm{cut}}^{\pi\pi}$ is the expected number of $\pi\pi$ events after cuts and efficiency corrections. The systematic error on $\Gamma_{\gamma\gamma}$ (19% fractional error) comes dominantly from $\delta\mathscr{L}'$ the normalisation uncertainty. Statistical errors of 3.1%, 2% in $\delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}$ are given by δN_{TOT} and, $\delta\sigma_{\mathrm{cut}}^{\mathrm{QED}}$ (Monte-Carlo statistics) respectively. Adding in quadrature the statistical errors it is found that:

$$\Gamma_{\gamma\gamma}(f_0)=2.5\pm0.1\,(\mathrm{stat})\pm0.5\,(\mathrm{syst})\ \mathrm{keV}.$$

Including VDM form factors with the rho mass increases this value by $\simeq 2\%$.

6. Physics Consequences of $\Gamma_{\gamma\gamma}(f_0)$ and Related Measurements

Results for $\Gamma_{\gamma\gamma}(f_0)$ of this and previous published experiments are summarised in Table 1. In all cases pure helicity 2 production of the f_0 is assumed. Our result is consistent with the average of the previous

Table 1. Measurements of $\Gamma_{\gamma\gamma}(f_0)$

Exp.	Ref.	$\Gamma_{\gamma\gamma}(f_0)$ (keV)	σ_{stat} (keV)	σ_{syst} (keV)	Decay Channel
PLUTO	8	2.3	0.5	0.35	$\pi^+\pi^-$
MARK II	9	3.6	0.3	0.5	$\pi^+\pi^-$
TASSO	10	3.2	0.2	0.6	$\pi^+\pi^-$
Crystal Ball	5	2.7	0.2	0.6	$\pi^0\pi^0$
CELLO	this exp.	2.5	0.1	0.5	$\pi^+\pi^-$

experiments. The updated weighted world average value (statistical and systematic errors added in quadrature) is:

$$\Gamma_{\gamma\gamma}(f_0)=2.85\pm0.26\ \text{keV}.$$

The quark model gives predictions for the ratios of the radiative width of the mesons within a given $SU(3)$ flavour multiplet, when it is assumed that all members of the nonet have the same wave function at the origin (nonet symmetry) and that the amplitude is proportional to the square of the quark charges. Ideal mixing for the tensor nonet implies the absence of strange quarks in the wave functions of the f_0, A_2 and the absence of non strange quarks in the f'. Assuming that the radiative width scales with mass as m^3 it is found that:

$$\frac{\Gamma_{\gamma\gamma}(A_2)}{\Gamma_{\gamma\gamma}(f_0)}=0.40.$$

Combining the value of $\Gamma_{\gamma\gamma}(f_0)$ found here with our previously measured value of $\Gamma_{\gamma\gamma}(A_2)$ [4] we find:

$$\frac{\Gamma_{\gamma\gamma}(A_2)}{\Gamma_{\gamma\gamma}(f_0)}=0.32\pm0.13\ \text{(Experiment)}.$$

This is in agreement with the above theoretical expectation, but our errors are too large to make a meaningful measurement of the singlet/octet mixing angle. The measurement of $\Gamma_{\gamma\gamma}(f')$ in [6] is also in good accord with ideal mixing, the non-strange quark admixture in the f' wave function being limited to a few percent.

Several attempts have been made within the quark model, to go beyond symmetry relations and to actually calculate $\Gamma_{\gamma\gamma}(f_0)$ by using potential models, either a harmonic oscillator model [29, 30] or more recently a relativistic calculation using the Bethe-Salpeter equation [31]. The non relativistic calculations agree well with our measurement. The relativistic calculation [31] gives a prediction which is a factor 2.8 times smaller than our results.

A large number of other attempts were made (see [1]) to calculate $\Gamma_{\gamma\gamma}(f_0)$ using Tensor Meson Dominance, Dispersion Relations or Finite-Energy Sum Rules. The last two approaches relied on duality between s and t channel exchanges. Typically such calculations predicted values between 2 and 10 times larger than now found experimentally.

In some cases [25, 33] more precise input data has brought these predictions into accord with experiment [32, 34]. Some ambiguities remain however. For example [25, 32] using Finite Energy Sum Rules and Harari Freund Duality (neglect of the Pomeron contribution) find $\Gamma_{\gamma\gamma}(f_0)=3.0$ keV in agreement with experiment. However [26] making the orthogonal assumption that the f_0 is dual to the Pomeron found $\Gamma_{\gamma\gamma}(f_0)\simeq2.1$ keV when pure helicity 2 coupling is assumed, also in reasonable agreement with experiment.

The radiative widths of all the lowest lying 0^- and 2^+ states have now been experimentally measured. This enables a test to be made, in the resonance saturation approximation, of the superconvergence sum rule [35]:

$$\int_0^\infty \frac{ds}{s}\left[\sigma(s)^{\lambda=0}-\sigma(s)^{\lambda=2}\right]=0 \tag{10}$$

where $\sigma(s)^\lambda$ is the total cross section for real photon photon collision in a state of total helicity λ and total centre of mass energy $\sqrt{s}$. The sum rule equation (10) is derived from rather weak convergence assumptions [26] and has been shown to be automatically satisfied for both the Born term and the quark box diagram [36]. In particular no contribution from a fixed pole [36, 37] is expected in this case.

In the narrow resonance approximation each distinct resonance gives a contribution $8\pi^2\xi(2J_R+1)$ $\Gamma_{\gamma\gamma}/m_R^3$ to the sum rule where m_R is the mass of the resonance J_R its spin and ξ is $+1$ for $J_R=0$ or $J_R=2$, $\lambda=0$ and -1 for $J_R=2$, $\lambda=2$. The narrow resonance approximation is expected to be good for the 0^- states π^0, η, η' which are indeed narrow and non-overlapping. For the tensor states however, where the dominant contribution comes from the f_0, this approximation is expected to be poorly satisfied because of the large width of the f_0 and the strong interference effects which occur between the f_0 and the Born term in the $\lambda=2$ amplitude (Fig. 6). In evaluating the sum rule the contributions of the Born term and the f_0 are therefore taken from the partial wave amplitudes that correspond to the best fit to our data shown in Fig. 2. The A_2, f' (which contribute only $\approx30\%$ of the f_0) and the pseudoscalars are treated in the narrow resonance approximation using values of $\Gamma_{\gamma\gamma}$ taken from [2–11]. With these inputs the sum of the unmeasured contri-

butions to the sum rule may be evaluated. Assuming $\lambda=2$ dominance of tensor meson production these are:
(i) Scalar mesons
(ii) Other contributions, except the Born term, e.g. $\gamma\gamma\to\rho^0\rho^0$ [38, 39], non resonant backgrounds, high p_T processes [40].

Treating (i) in narrow resonance approximation and denoting the sum of all contributions in (ii) as S_x (10) may be written as:

$$S_x+8\pi^2 \sum_{i=\delta,\sigma,\varepsilon} \frac{\Gamma_{\gamma\gamma}(i)}{m_i^3}=(8\pm16)\times10^{-11}\,\mathrm{MeV}^{-2}. \qquad (11)$$

For comparison the contribution of the f_0 alone to the sum rule, neglecting interference effects is $55\times10^{-11}\,\mathrm{MeV}^{-2}$. An important contribution to S_x comes from $\gamma\gamma\to4\pi$ which has both $\langle s\rangle$ and $\langle\sigma\rangle$ close to that for the sum of the tensor mesons [41]. The TASSO result [42] that $\gamma\gamma\to\rho^0\rho^0\to4\pi$ is predominantly in the 0^+ state at low masses indicates that the contribution to S_x from this channel should be positive. In this case (11) suggests that (modulo large and unknown $\lambda=2$ terms in S_x) $\Gamma_{\gamma\gamma}(i)$ is small for the low mass scalar states. Suppression of the 2γ coupling of scalar states has been predicted by a number of authors [43–45, 27] while others [25, 46] have predicted very large values ≈ 20 keV for the radiative widths of scalar mesons at variance both with (11) and direct measurement of the TASSO experiment for the $\varepsilon(1300)$ [10]

$$\Gamma_{\gamma\gamma}(\varepsilon)\cdot B(\varepsilon\to\pi^+\pi^-)<1.5\,\mathrm{keV}\ \ (95\%\ \mathrm{C.L.}).$$

It is interesting to note that the sum rule equation (10) has been formerly used [47, 48] to derive a value for $\Gamma_{\gamma\gamma}(f_0)$ of 9.2 keV. It was then argued [47, 48] that the resonance contribution to the total $\gamma\gamma$ cross section was too large to satisfy Regge resonance duality. The much smaller measured value of $\Gamma_{\gamma\gamma}(f_0)$ and the suppression of the radiative widths of the scalar mesons indicated by (11) invalidate this argument.

For further elucidation of the sum rule in (11) more precise experimental measurements of $\Gamma_{\gamma\gamma}$ for the scalar states is desirable. The analysis now being performed on our dipion data in the mass region between 400 and 800 MeV/c^2 should give more evidence on this question. Improved spin parity measurements for $\gamma\gamma\to4\pi$ as a function of s will serve to limit the S_x term in (11).

7. Summary and Conclusions

The model of Mennessier using only a unitarised Born term and a helicity 2 f_0 amplitude for the process $\gamma\gamma\to\pi^+\pi^-$ gives a good fit to our $\pi^+\pi^-$ data in the mass region $0.8<M_{\pi\pi}<1.5\,\mathrm{GeV/c^2}$. The only adjustable parameter, the radiative width of the f_0, is determined to be:

$$\Gamma_{\gamma\gamma}(f_0)=2.5\pm0.1\ (\mathrm{stat})\pm0.5\ (\mathrm{syst})\ \mathrm{keV}.$$

The distortion and downward shift ($\approx 50\,\mathrm{MeV/c^2}$) of the f_0 peak are explained by strong interference effects between the Born and f_0 amplitudes.

Our measured ratio $\Gamma_{\gamma\gamma}(A_2)/\Gamma_{\gamma\gamma}(f_0)$ is consistent with nonet symmetry and ideal mixing. Using the fit to our data to estimate the Born term and f_0 contributions to the sum rule equation (10) we find the 2γ couplings of the low mass scalar mesons to be suppressed unless there are large (as yet unknown) $\lambda=2$ terms in the sum rule.

Acknowledgments. We would like to thank Dr. G. Mennessier for many useful and enlightening discussions, and for supplying us with a copy of his programme for calculating dipion production in real photon-photon collisions. We are indebted to the PETRA machine group, the DESY computer centre, and the CCPN Paris for their excellent support during the data taking and analysis stages of the experiment. We acknowledge the important contributions of all engineers and technicians of the collaborating institutions in the construction and maintenance of the apparatus, in particular the operation of the magnet system by G. Mayaux and Dr. Horlitz and their groups. The visiting groups wish to thank the DESY directorate for the support and kind hospitality extended to them. This work was partly supported by the Bundesministerium für Forschung und Technologie.

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