Pion and Kaon Pair Production in Photon-Photon Collisions

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We report measurements of the two-photon processes $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ and $e^+e^- \rightarrow e^+e^-K^+K^-$, at an e^+e^- center-of-mass energy of 29 GeV. In the $\pi^+\pi^-$ data a high-statistics analysis of the $f(1270)$ results in a $\gamma\gamma$ width $\Gamma(\gamma\gamma \rightarrow f) = 3.2 \pm 0.4$ keV. The $\pi^+\pi^-$ continuum below the f mass is well described by a QED Born approximation, whereas above the f mass it is consistent with a QCD-model calculation if a large contribution from the f is assumed. For the K^+K^- data we find agreement of the high-mass continuum with the QCD prediction; limits on $f'(1520)$ and $\theta(1720)$ formation are presented.

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The study of photon-photon production of continuum $\pi^+\pi^-$ and K^+K^- final states has been suggested to test a QCD calculation in a model proposed by Brodsky and Lepage.[1] In the process $\gamma\gamma \rightarrow \pi^+\pi^-$ the observation of the continuum is complicated by a major contribution from the resonance $f(1270)$. The onance $f'(1520)$ does not contribute nearly as much to the process $\gamma\gamma \rightarrow K^+K^-$ because of its small $\gamma\gamma$ width; therefore the K^+K^- final state is perhaps more suited to test the prediction than the $\pi^+\pi^-$ final state. Resonance formation by two photons is an area of interest in its own right: Predictions of SU(3) symmetry[2] can be tested and possible gluonium admixtures[3] can be investigated by study of the relative coupling strengths of the photons to resonances within a given nonet, as manifested by their $\gamma\gamma$ widths.

The reaction $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-\pi\pi$ has been measured by several experiments over the last six years.[4-9] In these experiments the attention was mainly focused on the formation of the $f(1270)$. Edwards *et al.*[7] have published results using the decay into $\pi^0\pi^0$. A common problem in the other experiments (detecting the charged decay mode) has been the elimination of the dominant backgrounds from the QED reactions $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ and $e^+e^- \rightarrow e^+e^-e^+e^-$. Courau *et al.*[8] used Čerenkov counters to reject the $e^+e^-e^+e^-$ final state, while Berger *et al.*[9] used explicit lepton identification in two limited kinematical regions. The other experiments generally used Monte Carlo simulations. Results on the reaction $e^+e^- \rightarrow e^+e^-K\bar{K}$ have been published by Althoff *et al.*[10] High-statistics results on the combined $\pi^+\pi^-$ and K^+K^- continuum have been published recently by Boyer *et al.*[11]

We present here the results of an analysis performed by the TPC/Two-Gamma Collaboration in which the $\pi^+\pi^-$ and K^+K^- final states were treated separately.[12] Extensive use was made of the particle-identification capabilities of the time projection chamber (TPC) by measurement of the energy loss dE/dx. The analysis is based on data collected at an e^+e^- center-of-mass energy of 29 GeV using the SLAC e^+e^- storage ring PEP and the TPC/two-gamma detector.[13] The sample corresponds to an integrated luminosity of 74.6 pb^{-1} of untagged data (i.e., data where the final-state e^+ and e^- are not detected) and 24.6 pb^{-1} of singly tagged data (i.e., data where one final-state e^+ or e^- is detected).

Events were selected with exactly two oppositely charged prongs coming from the vertex, each with a $|p_\perp| \geqslant 200$ MeV/c and polar angle $\theta \geqslant 640$ mrad in the TPC. A tagged event had one e^+ or e^- (the tag) with an energy $E \geqslant 2.2$ GeV in a forward detector ($25 \leqslant \theta \leqslant 180$ mrad). To ensure the exclusivity of the event, a $|\Sigma p_\perp|$ cut was imposed ($\leqslant 150$ MeV/c for $\mu^+\mu^-/\pi^+\pi^-$ events without tag, and $\leqslant 400$ MeV/c for e^+e^- and K^+K^- events and events with a tag, tag included). Nearly all two-prong events were individually identified as e^+e^-, K^+K^-, $p\bar{p}$, or $\mu^+\mu^-/\pi^+\pi^-$. A μ-π separation cannot be made on an event-to-event basis. Rather, the separation can be made statistically, from dE/dx information at $\gamma\gamma$ invariant masses M between 0.4 and 0.8 GeV/c^2 and from muon-detector information at masses greater than 1.3 GeV/c^2. A Monte Carlo calculation, normalized to the above two regions, was used to estimate the number of $\mu^+\mu^-$ events, $N^{\text{est}}_{\mu^+\mu^-}$, for the full mass region from 0.8 to 2.0 GeV/c^2.

In this mass region the function

$$N(M) = AN^{\text{est}}_{\mu^+\mu^-}(M)\left\{1 + \frac{\int R_\epsilon(M,\cos\theta^*)[d\sigma_{\gamma\gamma\rightarrow\pi^+\pi^-}(M,\cos\theta^*)/d\Omega^*]d\Omega^*}{\int [d\sigma_{\gamma\gamma\rightarrow\mu^+\mu^-}(M,\cos\theta^*)/d\Omega^*]d\Omega^*}\right\} \tag{1}$$

was fitted to the combined $\mu^+\mu^-/\pi^+\pi^-$ data sample for each of several chosen ranges of $\cos\theta^*$ (θ^* is the angle of one of the prongs with respect to the $\gamma\gamma$ axis in the $\gamma\gamma$ center of mass). The $\pi^+\pi^-$ results are therefore relative to the QED cross section for two-photon μ-pair production, with the advantage that acceptance effects are similar for the $\pi^+\pi^-$ and $\mu^+\mu^-$ final states and tend to cancel. The ratio of the acceptance for pions to that of the muons, R_ϵ, was calculated from the Monte Carlo results. The $\pi^+\pi^-$ cross section is taken to be

$$d\sigma_{\gamma\gamma\rightarrow\pi^+\pi^-}(M)/d\Omega^* = |F|^2 + |G|^2 + |g(\Gamma_{\gamma\gamma\rightarrow f})|^2 + 2|G|\text{Re}\,g(\Gamma_{\gamma\gamma\rightarrow f})I, \tag{2}$$

where the first two terms are the QED Born expressions for helicities 0 and 2, respectively. For the resonance amplitude, g, a relativistic Breit-Wigner form was used, with an energy-dependent width and helicity 2 (as used in, for example, Refs. 6 and 8). The three parameters involved are the $\gamma\gamma$ width of the f ($\Gamma_{\gamma\gamma\rightarrow f}$), a factor ($I$) multiplying the interference term, and a normalization parameter (A), multiplying the statistically obtained $\mu^+\mu^-$ spectrum $N^{\text{est}}_{\mu^+\mu^-}$.

For the untagged data, the resulting cross section in the angular range $|\cos\theta^*| \leqslant 0.6$ is shown in Fig. 1 as the solid line. Also shown are the data points with effects of the mass resolution [$\sigma(M)/M = 3\%$–4% in this mass range] removed. The resulting $\gamma\gamma$ width is

$$\Gamma(\gamma\gamma \rightarrow f) = 3.2 \pm 0.1 \pm 0.4 \text{ keV}, \tag{3}$$

where the systematic error is due to the determination of $N^{\text{est}}_{\mu^+\mu^-}$ and R_ϵ. This value is in agreement with the world average of 2.75 ± 0.26 keV.[14] That the assump-

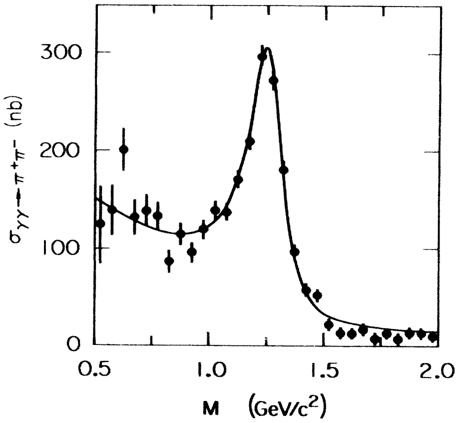

FIG. 1. The cross section for the process $\gamma\gamma \rightarrow \pi^+\pi^-$, corrected for mass resolution, for the angular range $|\cos\theta^*| \leqslant 0.6$, untagged data. Only statistical uncertainties are shown.

tion of helicity-2 formation is reasonable can be seen from Fig. 2(a), which shows the decay-angular distribution of the *f* along with expectations for helicities 0 and 2.

As observed in other experiments, the peak position is shifted down from the nominal value[14] of 1273 MeV. This can be attributed to interference of the *f* with the $\pi^+\pi^-$ continuum. The value of the interference parameter, averaged over all angular ranges, is $I = 0.50 \pm 0.11$. Taking the Born approximation literally, with I fixed at 1, leads to an unacceptable fit, as was also observed by the Mark II Collaboration.[5] The average value of the normalization parameter is $A = 1.03 \pm 0.04$. A deviation of this parameter from 1 would be expected if $N^{\text{est}}_{\mu^+\mu^-}$ were incorrect.

The result for the $\gamma\gamma$ cross section at low mass (≤ 1 GeV/c^2) is consistent with the prediction of the Born approximation (see Fig. 1). In a recent analysis, the PLUTO Collaboration[9] found their data between 0.5 and 0.7 GeV/c^2 to be significantly below the Born prediction. Our cross section in this mass range disagrees with the PLUTO result.

Similar fits were performed on the tagged data in the angular range $|\cos\theta^*| \leq 0.6$ in order to obtain the dependence of $\pi^+\pi^-$ production in the *f* region on the square of the invariant mass of the tagged photon, $-Q^2$. Because of limited statistics it was necessary, in each bin of Q^2, to keep the *f* helicity and all fit parameters fixed at the values obtained from the untagged data, with the exception of a form-factor parameter multiplying the entire $\gamma\gamma \to \pi^+\pi^-$ cross section and the parameter A. The resulting values of the form-factor parameter are plotted versus Q^2 in Fig. 2(b). The errors were determined by the fitting procedure; Q^2-dependent systematic errors are estimated to be less than 25%. The curves in Fig. 2(b) show predictions using form factors from the vector-meson-dominance model[15] (VDM) and generalized VDM (GVDM[16]). There is a preference for the VDM (ρ-pole) form factor.

The $\pi^+\pi^-$ cross section for the mass range 1.3–3.5 GeV/c^2 and angular range $|\cos\theta^*| \leq 0.3$ was obtained directly from the statistical method using the muon detector, also relative to the QED cross section for $\gamma\gamma \to \mu^+\mu^-$. It is shown as a function of M in Fig. 3(a), where an estimated systematic error of 20% has

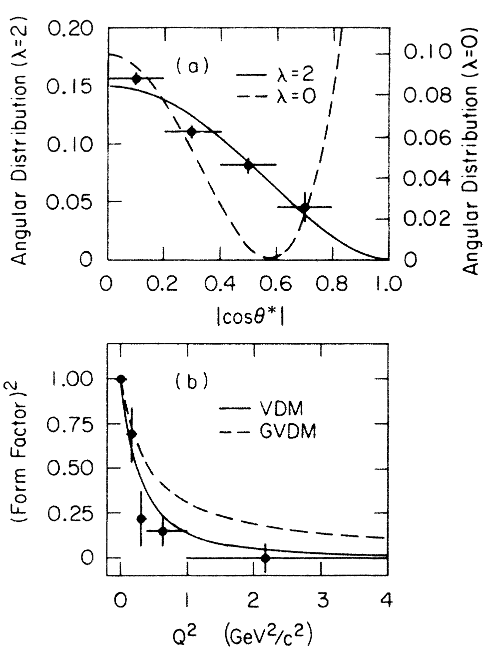

FIG. 2. (a) Angular distribution of one of the pions from the *f* decay with respect to the photon-photon axis in the $\gamma\gamma$ center of mass. The solid (dashed) curve represents the best fit of a helicity $\lambda = 2$ (0) angular distribution to the data; the left (right) vertical scale is normalized so that the integral is unity. (b) The Q^2 dependence of $\pi^+\pi^-$ production in the *f* region from single-tag data. The solid line represents the expectation from vector dominance, the dashed line that from generalized vector dominance. Only statistical uncertainties are shown.

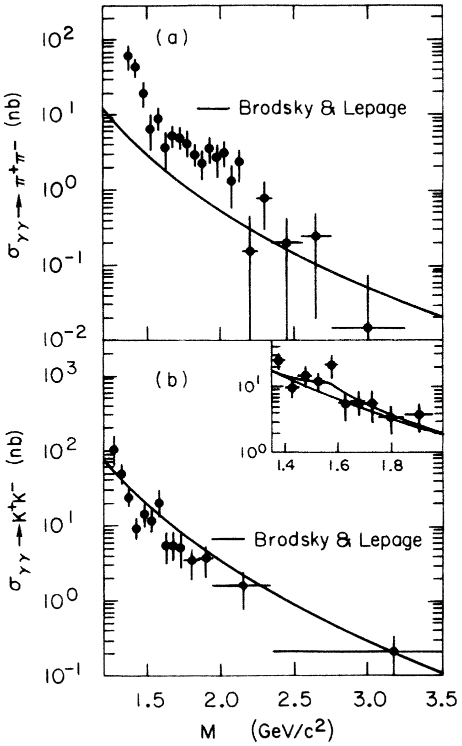

FIG. 3. The cross sections for the processes (a) $\gamma\gamma \to \pi^+\pi^-$ and (b) $\gamma\gamma \to K^+K^-$. The curves represent QCD calculations; see text. In (a) the angular range is $|\cos\theta^*| \leq 0.3$; in (b), $|\cos\theta^*| \leq 0.6$. Inset: The result of a fit using a Breit-Wigner form for the f' and the QCD curve with variable normalization.

not been included. The data are compared with the result of a perturbative-QCD calculation with absolute normalization[1] (solid line). The shape of the calculated curve seems to agree well with the data at masses above 1.5 GeV/c^2, but the absolute value is too low by a factor of about 2. At the low-mass end the data rise because of the presence of the f. It is likely that the f still contributes to the spectrum up to about 2 GeV/c^2; it is difficult to make a quantitative estimate because of interference effects.

For the process $\gamma\gamma \rightarrow K^+K^-$ the acceptance was obtained from a Monte Carlo simulation. The $\gamma\gamma$ cross section is given in Fig. 3(b). Only statistical errors are shown. Systematic uncertainties arise mainly from the accuracy of the simulation of the trigger efficiency and of the particle identification criteria used for the selection of this final state, and total about 20%. The solid line is again the QCD prediction. Here, the curve is in agreement with the data, in shape as well as in absolute value. The rise at low mass can be partly attributed to the presence of the f and the A_2 in their K^+K^- decay modes. The shoulder at around 1.5 GeV/c^2 may be due to the formation of the f'. A fit using a relativistic Breit-Wigner shape for the f' and the QCD continuum with variable normalization resulted in a $\gamma\gamma$ width times branching ratio into $K\overline{K}$ of $0.12 \pm 0.07 \pm 0.04$ keV, or a 95% confidence level upper limit of 0.28 keV, in agreement with the value of $0.11 \pm 0.02 \pm 0.04$ keV obtained by the TASSO Collaboration.[10] The result of the fit is shown as an inset in Fig. 3(b). When a relativistic Breit-Wigner form (spin 2, helicity 2) for the $\theta(1720)$ is included, an upper limit for its $\gamma\gamma$ width times branching ratio into K^+K^- of 0.10 keV is obtained.

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