Measurement of the pion form factor at $640 \leqslant \sqrt{s} \leqslant 1400$ MeV

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(Submitted 5 May 1983)

Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 12, 613–617 (20 June 1983)

The electromagnetic form factor of the pion has been measured over the energy range 640–1400 MeV with the OLYa detector on the VÉPP-2M storage ring in the reaction $e^+e^- \to \pi^+\pi^-$. The characteristics of the ρ meson and of the ρ–ω interference have been found. At $\sqrt{s} > 1000$ MeV the pion form factor cannot be described as the sum of ρ and ρ' (1600) mesons.

PACS numbers: 13.40.Fn, 13.65. + i, 14.40.Aq

In this letter we report a continuation of a study begun in Ref. 1., of the pion form factor with the OLYa detector. The detector is described in Ref. 2; preliminary results from an analysis of part of the statistical base (1060–1400 MeV) were published in Ref. 3. No important changes were made in the basic principles for analyzing the experimental data.

The statistical base was obtained by scanning the energy interval at a step roughly equal to the energy spread in the c.m. frame (0.5–0.7 MeV). The luminosity integral adopted in this experiment was about 1500 nb^{-1}, which is about an order of magnitude larger than has been used for any other detector in this energy range.

The first step of the analysis was to select events with two tracks in the coordinate chambers which emerge from the volume in which the e^+ and e^- beams interact and which satisfy the collinearity conditions

$$|\Delta\theta| < 7^\circ, \quad |\Delta\phi| < 5^\circ \quad (\sigma_{\Delta\phi,\,\Delta\theta} \sim 1^\circ).$$

Furthermore, at least one of the particles had to reach the first counter of the sandwich (23 g/cm^2). This condition substantially reduced the background from the reaction $e^+e^-\to e^+e^-e^+e^-$. In the same step of the analysis, we eliminated $e^+e^-\to K^+K^-$ events on the basis of the high specific ionization loss in the scintillation counters.[4]

The 880×10^3 events which survivd these conditions were classified as $e^+e^-\to\pi^+\pi^-, \mu^+\mu^-$ events and elastic-scattering events $e^+e^-\to e^+e^-$ by the correlation-matrix method[5] in accordance with the heights of the signals from the scintillation counters of the sandwich. The $e^+e^-\to\pi^+\pi^-$ and c $e^+e^-\to\mu^+\mu^-$ events were classified on the basis of the ranges of the particles in the shower—range system. Over the entire energy interval, we found $N(e^+e^-) = 698\times 10^3$, $N(\mu^+\mu^-) = 43\times 10^3$, and $N(\pi^+\pi^-) = 139\times 10^3$ events.

The detection efficiencies for these reactions were calculated by the experimental simulation program described in Ref. 6. Radiation corrections for these proceses were found in accordance with Ref. 7.

The primary source of background for the reaction $e^+e^-\to\pi^+\pi^-$ is the reaction $e^+e^-\to e^+e^-e^+e^-$, whose cross section depends only slightly on the energy. The magnitude of this background was 0.1% at $\sqrt{s}\sim m\rho$, increasing to 25% at $\sqrt{s} = 1400$ MeV. The number of events corresponding to this reaction was determined from the number of events with soft particles, which had been rejected previously, and from the scaling factor found from the simulation. We also subtracted a small admixture of $e^+e^-\to\pi^+\pi^-\pi^+\pi^-$ and $e^+e^-\to\pi^+\pi^-\pi^0\pi^0$ events. The magnitude of this admixture was determined from the experimental cross sections found in our earlier experiments.[8]

The ratio of the number of $\mu^+\mu^-$ events to the number of e^+e^- events detected in this experiment, divided by the value predicted for this ratio by quantum electrodynamics, is

$$\frac{[N(\mu^+\mu^-)/N(e^+e^-)]_{\text{expt}}}{[N(\mu^+\mu^-)/N(e^+e^-)]_{\text{QED}}} = 1.02 \pm 0.01 \pm 0.03.$$

The statistical and systematic errors are given. This good agreement between the experimental results and quantum electrodynamics supports the analysis method used here.

Figure 1 shows the experimental values of $|F_\pi|^2$ as a function of the energy. The values found for $|F_\pi|^2$ in this experiment agree with our own earlier results and results reported by other groups.[1,9-13]

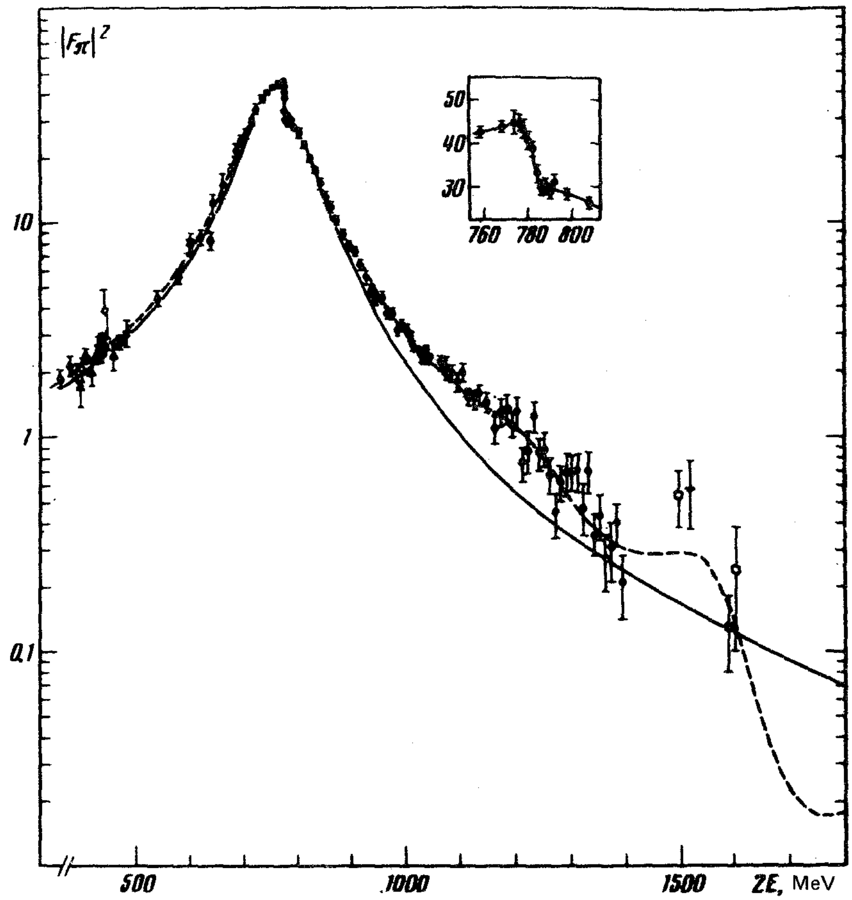

FIG. 1. Experimental values of $|F_\pi|^2$ found in several studies. □—Ref. 17; ■—Ref. 12; —Ref. 13; ×—Ref. 10; ▲—Ref. 15; ○—Ref. 14; ◆—Ref. 16; ●—present experiment. The solid curve is plotted from the Gounaris-Sakurai formula with the ρ–ω interference; the dashed curve shows a parametrization of $F_\pi(s)$ incorporating the ρ, ω, ρ' (1250), and ρ'' (1600) mesons with the optimum parameter values.

Analysis of the possible sources of systematic errors in the present experiment showed that the systematic error in $|F_\pi|^2$ is about 4% at $\sqrt{s} = 800$ MeV, increasing to 15% at $\sqrt{s} = 1400$ MeV.

To explain why $|F_\pi|^2$ exceeds the ρ-meson tail we compared the experimental results with the predictions of several models which describe the pion form factor. The following data were incorporated in this comparison: the data of Refs. 10 and 14–16 for $\sqrt{s} < 640$ MeV, the data from the present experiment over the interval 640–1400 MeV, the data of Refs. 12, 13, and 17 for 1400–1700 MeV, and the data of Refs. 18 and 19 for $\sqrt{s} > 3000$ MeV.

We first considered a model incorporating ρ' (1600), whose existence can be considered reliably established, as can the decay $\rho' \to \pi^+\pi^-$ (Ref. 20). We fitted the experimental data with $m_{\rho'} = 1600 \pm 20$ MeV, $\Gamma_{\rho'} = 300 \pm 100$ MeV, and adjustable $B_{\rho'\pi\pi}\Gamma_{\rho'ee}$, and an adjustable relative phase $\psi_{\rho\rho'}$, but we were not able to find a satisfactory description of the experimental data. The addition of yet another resonance—ρ' (1250), which has been discussed in the literature for a long time, results in a good agreement of the curve with the experimental points.

The pion form factor was parametrized by

$$F_\pi(s) = F_\pi^\rho \,(1 + \eta e^{i\theta_{\rho\omega}} F_\pi^\omega) + \xi_1 e^{i\psi_1} F_\pi^{\rho'} + \xi_2 e^{i\psi_2} F_\pi^{\rho''}),$$

where F_π^ρ, the ρ-meson contribution, was calculated from the Gounaris-Sakurai formula[21]; and F_π^ω, $F_\pi^{0'}$, $F_\tau^{\rho''}$—the terms corresponding to the ω, ρ' (1250), and ρ'' (1600) mesons—were calculated from the Breit-Wigner formula. The quantities m_ρ, Γ_ρ $\theta_{\rho\omega}$, η, $m_{\rho'}$, $\Gamma_{\rho'}$, ξ_1, ξ_2 were free parameters. The optimum values of these parameters turned out to be

$m_\rho = 775.9 \pm 1.0$ MeV,	$m_{\rho'} = 1292 \pm 17$ MeV,
$\Gamma_\rho = 148.8 \pm 2.3$ MeV,	$\Gamma_{\rho'} = 218 \pm 46$ MeV,
$B_{\omega\pi\pi} = 2.03 \pm 0.45$ %,	$B_{\rho'\pi\pi}\Gamma_{\rho' ee} = 27^{+15}_{-10}$ eV,
$\theta_{\rho\omega} = 5.0 \pm 6.3°$,	
$\Gamma_{\rho ee} = 6.88 \pm 0.18$ keV,	$B_{\rho''\pi\pi}\Gamma_{\rho'' ee} = 29^{+16}_{-12}$ eV.

The relative phases ψ_2 and ψ_2 were taken to be 180°, and we adopted $F_\pi(0) = 1$.

It should be noted that, by themselves, the results of the present experiments yield only the upper limit

$$B(\rho''(1600) \to \pi^+\pi^-) \cdot \Gamma(\rho''(1600) \to e^+e^-) < 40 \text{ eV} \quad (90\% \text{ confidence level}),$$

unless we also consider the data for the interval 1400–1700 MeV. With ψ_1 and ψ_2 free, this upper limit rises to 240 eV.

Baĭer and Fadin[22] have proposed another explanation for the behavior of F_π. They were first to note that a rapid growth of the cross sections for many-hadron reactions in this energy range could lead to the necessary increase in $|F_\pi|^2$. Various possibilities for describing F_π through the use of many-hadron mechanisms were examined in Refs. 23–25, but ρ'' (1600) was ignored. Unfortunately, this effect cannot be described satisfactorily by taking ρ'' (1600) into account or even by taking into account the coupling of the $\pi^+\pi^-$ channel with various many-hadron channels. Nevertheless, we have now been able to achieve a fit with a simple parametrization[25] of $F_\pi(s)$ incorporating many-hadron channels. This parametrization was used in the experiment of Ref. 10. Furthermore $F_\pi(s)$ was approximated by a formula similar to that found in Ref. 23, but the ρ'' (1600) meson was considered in the $\pi^+\pi^-$ channel. It turns out that either of the models gives a satisfactory description of the experimental data at the optimum parameter values. The question of the existence of the ρ' (1250) meson thus remains open.

The optimum parameters of the ρ meson and the ρ–ω interference depend on the method used to describe $F_\pi(s)$. For the models considered here, the maximum scatter in the parameter values is given by

$\Delta m_\rho \approx 1$ MeV, $\Delta\Gamma_\rho \approx 2$ MeV, $\Delta B_{\omega\pi\pi} \approx 0.15\%$, $\Delta\Gamma_{\rho ee} \approx 0.3$ keV.

An important physical parameter associated with the pion form factor is its mean square radius $\langle r_\pi^2 \rangle$, which can be calculated from the optimum parameter values which we have found: $\langle r_\pi^2 \rangle = 0.423 \pm 0.004 \pm 0.015$ F^2. The first of the errors given here includes the statistical and systematic errors of the experiment; the second error is determined by the scatter in the values of $\langle r_\pi^2 \rangle$ in one of these models.

We wish to thank the VÉPP-2M staff for maintaining the complex in good operation. We also thank A. I. Vaĭnshteĭn and I. B. Khriplovich for useful discussions.

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Translated by Dave Parsons
Edited by S. J. Amoretty