Exclusive dipion production

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The exclusive electroproduction of two pions in the mass range $0.4 < \mathrm{M}_{\pi\pi} < 2.5$ GeV has been studied with the ZEUS detector at HERA using an integrated luminosity of 82 pb^{-1}. The two-pion invariant-mass distribution is interpreted in terms of the pion electromagnetic form factor, $|F(M_{\pi\pi})|$, assuming that the studied mass range includes the contributions of the ρ, ρ' and ρ" vector-meson states.

1 Exclusive dipion production

Exclusive electroproduction of vector mesons takes place through a virtual photon γ^* by means of the process $\gamma^* p \to Vp$. At large values of the centre-of-mass energy, W, this is usually viewed as a three-step process; the virtual photon γ^* fluctuates into a $q\bar{q}$ pair which interacts with the proton through a two-gluon ladder and hadronizes into a vector meson, V.
Exclusive $\pi^+\pi^-$ production has been measured at HERA [1] experiments: ZEUS [2, 3] and H1 [4] as well as in the annihilation process $e^+e^- \to \pi^+\pi^-$ [5, 6]. The $\pi^+\pi^-$ mass distribution shows a complex structure in the mass range 1–2 GeV. Evidence for two excited vector-meson states has been established [7]; the $\rho'(1450)$ is assumed to be predominantly a radially excited $2S$ state and the $\rho''(1700)$ is an orbitally excited $2D$ state, with some mixture of the S and D waves [8]. In addition there is also the $\rho_3(1690)$ spin-3 meson [9] which has a $\pi\pi$ decay mode.

1.1 Data selection

The data used in this analysis were collected at the HERA ep collider during 1998-2000 with the ZEUS detector. At that time HERA operated at a proton energy of 920 GeV and at a positron energy of 27.5 GeV. The integrated luminosity used was 82 pb^{-1}.

The data are selected in the two-pion mass range $0.4 < \mathrm{M}(\pi\pi) < 2.5$ GeV, in the kinematic range $2.5 < \mathrm{Q}^2 < 80$ GeV^2, 32<W<180 GeV and |t|<0.6 GeV^2, where Q^2 is the virtuality of the photon and t is the squared four-momentum transfer at the proton vertex. The $M_{\pi\pi}$ system consists of a resonance part and a non-resonant background.

1.2 Pion Form Factor

The resonances (ρ, ρ' and ρ'') are described by the pion form factor,F_π. It can be related to the $\pi\pi$ invariant-mass distribution through the following relation [10]:

$$\frac{dN(M(\pi\pi))}{dM_{\pi\pi}} \propto |F_\pi(M_{\pi\pi})|^2$$

In the mass range $M_{\pi\pi} < 2.5$ GeV, Kuhn-Santamaria (KS) [11] include contributions from the $\rho(770)$, $\rho'(1450)$ and ρ"(1700) resonances,

$$F_\pi = \frac{BW_\rho(M_{\pi\pi}) + \beta BW_{\rho'}(M_{\pi\pi}) + \gamma BW_{\rho"}(M_{\pi\pi})}{1+\beta+\gamma}.$$

Here β and γ are relative amplitudes and BW_V is the Breit-Wigner distribution of the vector meson V.

The $\pi^+\pi^-$ mass distribution, after acceptance correction, is shown in Figure 1. A clear peak is seen in the ρ mass range. A small shoulder is apparent around 1.3 GeV and a secondary peak at about 1.8 GeV.

The two-pion invariant-mass distribution was fitted, using the least-square method, as a sum of two terms,

$$\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} = A\left(1-\frac{4M_\pi^2}{M_{\pi\pi}^2}\right)\left[F_\pi + B\left(\frac{M_0}{M_{\pi\pi}}\right)^n\right],$$

where A is an overall normalization constant. The second term is a parameterization of the non-resonant background, with constant parameters B, n and $M_0 = 1$ GeV. The other parameters, the masses and widths of the three resonances and their relative contributions β and γ, enter through the pion form factor, F_π. The fit, which includes 11 parameters, gives a good description of the data.

The result of the fit is shown in Figure 1 together with the contribution of each of the two terms. The ρ and the ρ" signals are clearly visible. The negative interference between all the resonances results in the ρ' signal appearing as a shoulder.

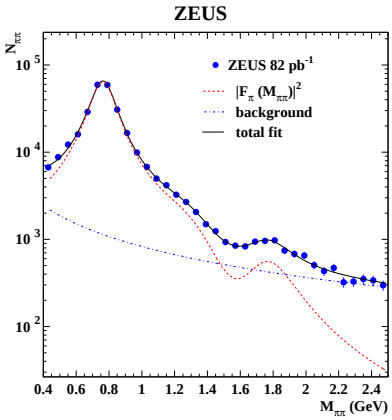

Figure 1: The two-pion invariant-mass distribution, $M_{\pi\pi}$, where $N_{\pi\pi}$ is the acceptance-corrected number of events in each bin of 60 MeV. The dots are the data and the full line is the result of a fit using the Kuhn-Santamaria parameterization. The dashed line is the result of the pion form factor normalized to the data, and the dash-dotted line denotes the background contribution.

1.3 Q^2 dependence

The Q^2 dependence of the relative amplitudes was determined by performing the fit to $M_{\pi\pi}$ in three Q^2 regions, 2–5, 5–10 and 10–80 GeV^2. The results are shown in Figure 2. A reasonable description of the data is achieved in all three Q^2 regions. The absolute value of β increases with Q^2, while the value of γ is consistent with no Q^2 dependence, within large uncertainties.

The Q^2 dependence of the ρ by itself is given elsewhere [2]. Since the $\pi\pi$ branching ratios of ρ' and ρ" are poorly known, the ratio R_V defined as

$$R_V = \frac{\sigma(V)\cdot Br(V\to\pi\pi)}{\sigma(\rho)},$$

has been measured, where σ is the cross section for vector-meson production, and $Br(V\to\pi\pi)$ is the branching ratio of the vector meson $V(\rho', \rho")$ into $\pi\pi$.

The ratio R_V for $V = \rho', \rho"$, as a function of Q^2 is presented in Figure 3.

Owing to the large uncertainties of $R_{\rho"}$, no conclusion on its Q^2 behaviour can be deduced, whereas $R_{\rho'}$ clearly increases with Q^2. This rise has been predicted by several models [12, 13, 14, 15, 16]. The suppression of the $2S$ state (ρ') is connected to a node effect, which results

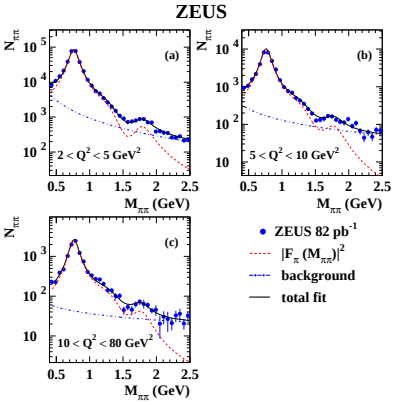

Figure 2: The two-pion invariant-mass distribution, $M_{\pi\pi}$ for three regions of Q^2, as denoted in the figure.

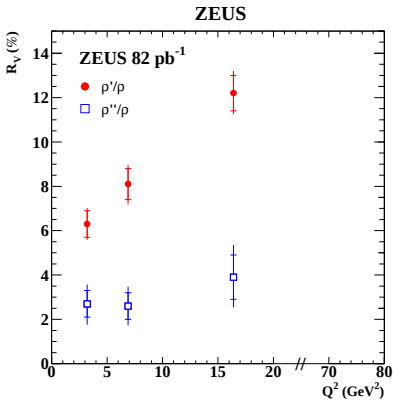

Figure 3: The ratio R_V as a function of Q^2 for $V = \rho'$ (full circles) and ρ" (open squares). The inner error bars indicate the statistical uncertainty, the outer error bars represent the statistical and systematic uncertainty added in quadrature.

in cancellations of contributions from different impact-parameter regions at lower Q^2, while at higher Q^2 the effect vanishes.

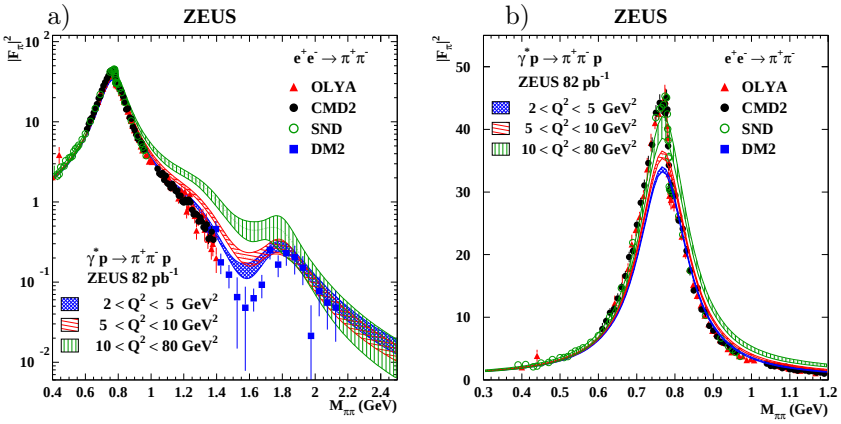

Figure 4: The pion form factor squared, $|F_\pi|^2$, in the whole mass range (a)) and in the ρ mass region (b)), as a function of the $\pi^+\pi^-$ invariant mass, $M_{\pi\pi}$, as obtained from the reaction $e^+e^- \to \pi^+\pi^-$ [5, 17, 18, 19, 20]. The shaded bands represent the square of the pion form factor and its total uncertainty obtained in the present analysis for three ranges of Q^2: 2–5 GeV^2(crossed lines), 5–10 GeV^2(horizontal lines) and 10–80 GeV^2 (vertical lines).

Figure 4 a) shows the curves representing the pion form factor, $|F_\pi(M_{\pi\pi})|^2$, as obtained in the present analysis for the three Q^2 ranges: 2–5, 5–10, 10–80 GeV^2. Also shown are results

obtained in the time-like regime from the reaction $e^+e^- \to \pi^+\pi^-$. In general, the features of the $|F_\pi(M_{\pi\pi})|^2$ distribution observed here are also observed in e^+e^-, i.e., the prominent ρ peak, a shoulder around the ρ' and a dip followed by an enhancement in the ρ" region. Above the ρ region, where the interference between the ρ' and the ρ" starts to dominate, there is a dependence of $|F_\pi(M_{\pi\pi})|^2$ on Q^2, with the results from the lowest Q^2 range closest to those from e^+e^-. However, in the region of the ρ peak, shown in Figure 4 *b*), the pion form-factor $|F_\pi(M_{\pi\pi})|^2$ is highest at the highest Q^2, as in the ρ'-ρ" interference region, while the e^+e^- data are higher than those in the highest Q^2 range. They are equal within errors for $M_{\pi\pi} > 1.8$ GeV.

2 Summary

Exclusive two-pion electroproduction has been studied by ZEUS at HERA. The mass distribution is well described by the pion electromagnetic form factor, $|F_\pi(M_{\pi\pi})|^2$, which includes three resonances, ρ, $\rho'(1450)$ and $\rho''(1700)$.

A Q^2 dependence of $|F_\pi(M_{\pi\pi})|^2$ is observed, visible in particular in the interference region between ρ' and ρ''. The electromagnetic pion form factor obtained from the present analysis is lower (higher) than that obtained from $e^+e^- \to \pi^+\pi^-$ for $M_{\pi\pi} < 0.8$ GeV ($0.8 < M_{\pi\pi} < 1.8$ GeV). They are equal within errors for $M_{\pi\pi} > 1.8$ GeV.

The Q^2 dependence of the cross-section ratios $R_{\rho'} = \sigma(\rho' \to \pi\pi)/\sigma(\rho)$ and $R_{\rho''} = \sigma(\rho'' \to \pi\pi)/\sigma(\rho)$, has been studied. The ratio $R_{\rho'}$ rises strongly with Q^2, as expected in QCD-inspired models in which the wave-function of the vector meson is calculated within the constituent quark model, which allows for nodes in the wave-function to be present.

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