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Studies of the hadronic component of the photon light-cone wave function using exclusive di-pion events at HERA

ZEUS Collaboration

Abstract

Measurements of exclusive di-pion production using an integrated luminosity of 66.3 pb^{-1} taken with the ZEUS detector at HERA are presented. Events with photon virtualities satisfying $Q^2 > 2$ GeV^2 and with photon-proton centre-of-mass energies satisfying $40 < \text{W} < 120$ GeV are used for the analysis, provided the invariant mass of the di-pion system is greater than 1.2 GeV. Acceptance corrected distributions of the di-pion invariant mass and of the light-cone momentum distribution of the di-pion system are presented and interpreted within the framework of the light-cone wave function (LCWF) formalism, in which the photon contains both electromagnetic and hadronic Fock states.

1 Introduction

The internal structure of hadrons and photons is described through the light-cone wave functions (LCWF). These functions are constructed from the QCD light-cone Hamiltonian $H_{LC}^{QCD} = P^+P^- - P_\perp^2$, where $P^\pm = P^0 \pm P^z$ with P the momentum operators [1]. The LCWF ψ_h for a hadron h with mass M_h satisfies the relation: $H_{LC}^{QCD}|\psi_h\rangle = M_h^2|\psi_h\rangle$. The LCWFs are expanded in terms of a complete basis of Fock states having increasing complexity [1]. They have longitudinal light-cone momentum fractions $u_i = \frac{k_i^+}{p^+} = \frac{k_i^0+k_i^z}{p^0+p^z}$ with $\sum_{i=1}^n u_i = 1$ and relative transverse momenta $\vec{k}_{\perp i}$ with $\sum_{i=1}^n \vec{k}_{\perp i} = \vec{0}_\perp$. The index i runs over the particles contained in the relevant Fock state. The first term in the expansion is referred to as the valence Fock state.

The photon LCWF has two major components, the electromagnetic and the hadronic;

$$\begin{aligned}\psi_\gamma = a|\gamma_p\rangle + b|l^+l^-\rangle + c|l^+l^-\gamma\rangle + (other\ e.m.)\\ +d|q\bar{q}\rangle + e|q\bar{q}g\rangle + (other\ hadronic) + \ldots\ ,\end{aligned} \tag{1}$$

where $|\gamma_p\rangle$ describes the pointlike, bare photon and $|l^+l^-\rangle$ stands for $|e^+e^-\rangle$, $|\mu^+\mu^-\rangle$ etc. Each of these states is a sum over the relevant helicity components. The LCWF for the lowest Fock states is known [2,3] and, for $k_\perp^2 \gg \Lambda_{QCD}^2$, is expected to be similar for the electromagnetic and hadronic components.

The predicted LCWF for the electromagnetic component is based on quantum electrodynamics; it was recently measured by the ZEUS collaboration [4] and was found to be in agreement with the predictions. The LCWFs for the hadronic component are model dependent.

In the present work the measurement of the exclusive diffractive electroproduction of non-resonant $\pi^+\pi^-$ pairs in positron-proton collisions at HERA, $ep \to e\pi^+\pi^-p$, is reported (see Fig. 1). This is expected to be sensitive to the $|q\bar{q}\rangle$ component of the photon LCWF. The concept of both previous measurements [4–6] and the analysis presented here is based on the following argument. In high energy interactions, viewed in the rest frame of the target, the beam particle dissociates into its Fock state long before the interaction. The valence Fock component dominates, while the other terms are suppressed according to counting rules [7]. In forward scattering, the momentum configuration of the interacting Fock state is preserved and therefore the final state is expected to reflect the kinematics of the initial state, providing the process is exclusive. In the process investigated here, the quarks from the virtual photon are assumed to hadronise into a $\pi^+\pi^-$ pair after the interaction.

The results are presented in terms of acceptance-corrected distributions of the di-pion invariant mass, $M_{\pi\pi}$, and the longitudinal-momentum fraction carried by one of the pions,

u. The latter is compared with predictions based on calculations of the $q\bar{q}$ component of the photon LCWF, under the assumption that the measured cross section is proportional to the square of the photon wave function and that the pion momenta are equal to the momenta of the initial $q\bar{q}$ pair.

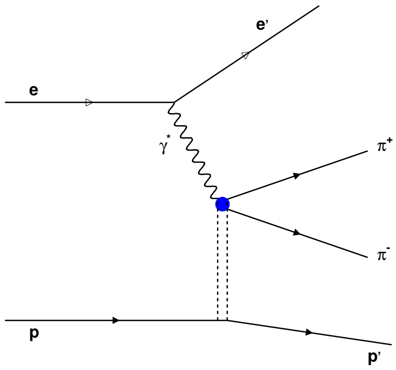

Figure 1: *A schematic diagram of the reaction $ep \to e\pi^+\pi^-p$.*

2 Data analysis

The data used in this analysis were collected at the HERA ep collider during 1999-2000 with the ZEUS [8] detector. At that time HERA operated at a proton energy of 920 GeV and a positron energy of 27.5 GeV. The data correspond to an integrated luminosity of 66.3 ± 1.7 pb^{-1}. The events were selected by requiring two oppositely-charged, well reconstructed tracks in the central tracking detector (CTD) [9], fitted to the interaction vertex and matched to energy deposits in the uranium calorimeter (CAL) citeCAL. Pions were identified using a neural network algorithm. The sum of the energy and longitudinal momentum of the scattered positron and the two pion candidates was required to satisfy $40 < E - p_Z < 60$ GeV. To select exclusive events, the total energy deposited in the CAL not associated to the scattered positron or the pion candidates was required to be less than 300 MeV. In order to limit the contribution from proton-dissociative events, $ep \to e\pi^+\pi^-N$, the energy deposited in the forward plug calorimeter (FPC) [11] was required to be less than 1 GeV. The FPC was located inside the forward CAL[1], close to the beam pipe. In the remaining events, the proton remains intact or diffractively dissociates into a low-mass state N.

[1] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the "forward direction", and the X axis pointing left towards the centre of HERA. The coordinate origin is at the nominal interaction point.

The kinematic region for this measurement is defined in terms of W, the $\gamma^* p$ centre-of-mass energy, Q^2, the photon virtuality, t, the square of the four momentum exchanged at the proton vertex and u, the longitudinal momentum-fraction carried by the negative pion. The formula for determining u is

$$u = \frac{E_1 + p_{z'_1}}{E_1 + E_2 + p_{z'_1} + p_{z'_2}}$$

where E_1, E_2 are the energies of the two pions and $p_{z'_1}, p_{z'_2}$ are the corresponding momentum components determined with respect to the axis z'. The z'-axis is the direction of the vector sum of the momenta of the two pions. The light-cone variables, u and $M_{\pi\pi}$, were reconstructed from the momenta of the CTD tracks.

The results are presented for the kinematic region $2 < Q^2 < 20$ GeV^2, $1.2 < M_{\pi\pi} < 5\,$GeV, $40 < W < 120\,$GeV, $|t| < 0.5\,$GeV^2 and $0.1 < u < 0.9$. The residual contamination (expected to be of the order of 14%) from proton-dissociative events was not subtracted. The acceptance corrections and resolution effects were determined using a dedicated Monte Carlo generator, ZEUSVM [12].

3 Results

Acceptance-corrected distributions of the data as a function of $M_{\pi\pi}$ and u are presented in Figs. 2 and 3 respectively. The systematic uncertainties are dominated by the uncertainties related to the trigger selection and the identification of the scattered positron.

The $M_{\pi\pi}$ distribution exhibits an approximately powerlike behaviour. A fit of the form $1/M_{\pi\pi}^n$ gives a value of $n \approx 4.5$.

The u distribution is presented for two Q^2 intervals and its shape is compared to the LCWF predictions for both transversely and longitudinally polarised photons. The normalisation for the longitudinal LCWF prediction was determined from a fit to the data. The normalisation of the transverse LCWF prediction was fixed to be the same as that for the longitudinal prediction at $u = 0.5$.

The u distribution is similar in the two intervals, and is consistent with the LCWF predictions for longitudinally polarised photons. The dominance of longitudinal photons has also been observed in the diffractive electroproduction of ρ^0 mesons [13]. The agreement between the measured u distributions and the predictions lends support to the assumption that non-resonant di-pion production is sensitive to the $q\bar{q}$ component of the light-cone wave function of the virtual photon.

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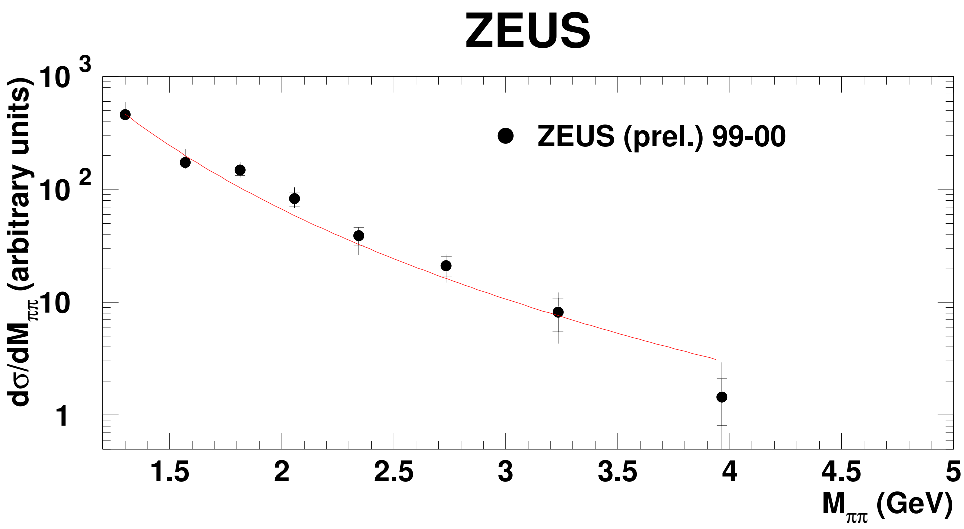

Figure 2: *The measured differential cross section $d\sigma/dM_{M_{\pi\pi}}$. The solid line indicates a fit to the form $1/M^n_{\pi\pi}$.*

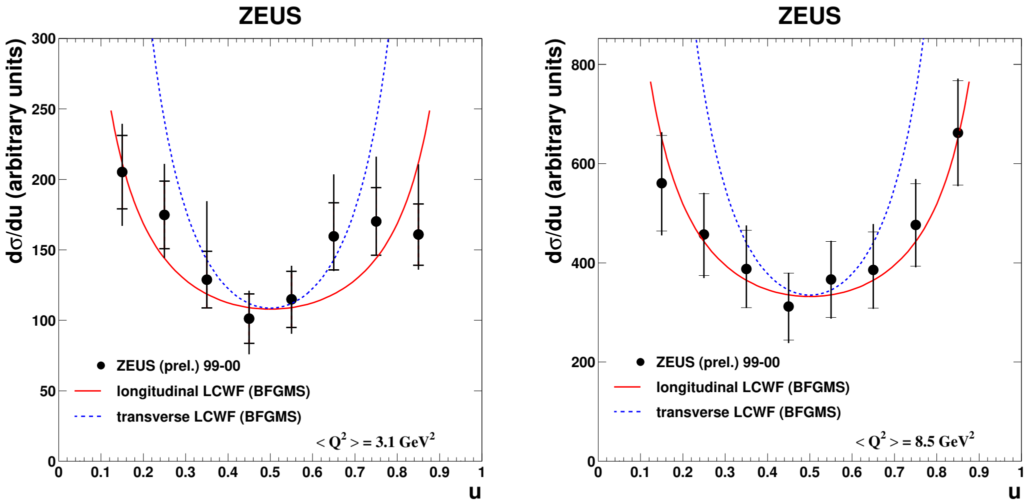

Figure 3: *The differential cross section $d\sigma/du$ measured in two different Q^2 intervals: $2 < Q^2 < 5$ GeV^2 (left) and $5 < Q^2 < 20$ GeV^2 (right). The inner error bars show the statistical uncertainties; the outer error bars show the statistical and systematic uncertainties added in quadrature. The data points are compared to the LCWF predictions [3], normalised to the data.*