Hard Exclusive Electroproduction of Two Pions off Proton and Deuteron at HERMES

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Abstract. Exclusive electroproduction of $\pi^+ \pi^-$ pairs off hydrogen and deuterium targets has been studied with the HERMES experiment. The angular distribution of the $\pi^+$ in the $\pi^+ \pi^-$ rest system has been studied in the invariant mass range $0.3 < m_{\pi\pi} < 1.5$ GeV. Theoretical models derived in the framework of the Generalized Parton Distributions show that this angular distribution receives only contributions from the interference between the isoscalar channel $I = 0$ and the isovector channel $I = 1$.

1. INTRODUCTION

The analysis of hard exclusive production of $\pi^+ \pi^-$ pairs off unpolarized targets of hydrogen and deuterium at HERMES is presented. Recent theoretical studies [1, 2, 3] have shown that the exclusive process $e^+ p \rightarrow e^+ p \pi^+ \pi^-$ can be described in the framework of Generalized Parton Distributions (GPDs) [4, 5, 6]. The diagrams relevant for this reaction at leading twist are shown in Fig. 1. The pion pairs may be produced through gluon or quark exchange with the target, either from quark (Fig. 1a,b,c) or from gluon fragmentation (Fig. 1d). In the range of the considered $\pi^+ \pi^-$ invariant mass ($m_{\pi\pi}$), both resonant and non-resonant contributions are present. The particular state describing the $\pi^+ \pi^-$ pair, with the angular momentum quantum number $l$ being odd or even, also defines unequivocally the quantum numbers C-Parity ($C$) and Strong Isospin ($I$) of this state. At small values of the Bjorken variable $x_{Bj}$, pions are produced mostly in the isovector state, because the dominant mechanism is two-gluon exchange with positive C-parity (Fig. 1a) [7]. At large $x_{Bj}$ the production of pion pairs is dominated by $q\bar{q}$

![FIGURE 1. Leading twist diagrams for the hard exclusive reaction $e^+ p \rightarrow e^+ p \pi^+ \pi^-$. The gluon exchange (a) gives rise to pions in the isovector state only, while the quark exchange (b,c,d) gives rise to pions both in the isoscalar and in the isovector state.](chart)
exchange (Fig. 1b,c,d) [8], which leads to a sizable admixture of pion pairs with isospin zero.

In the HERMES kinematics the $\pi^+\pi^-$ cross section is dominated by the isovector channel, i.e. $\rho^0$ production. The less copious isoscalar $\pi^+\pi^-$ production can be investigated by studying the interference between the odd and even $l$ wave production. An observable suitable to probe this interference appears to be the intensity density [2, 3], defined as the $l^\text{th}$ Legendre Polynomial $P_l(\cos \theta)$ moment

$$I P_l(\cos \theta) \frac{2}{\pi^l + \pi} x_{\pi^l + \pi} = \frac{1}{\pi^l + \pi} \left[ \frac{d \rho_{\pi^l + \pi}}{d \cos \theta} \right] \frac{d \rho_{\pi^l + \pi}}{d \cos \theta};$$

where $\theta$ is the scattering angle of $\pi^+$ meson in the $\pi^+\pi^-$ rest frame with respect to the direction of the recoiled system [8]. Some of the above defined intensities are non-zero only if the interference between the isoscalar and the isovector channels is present. Experimentally they are obtained as average values of $P_l(\cos \theta)$. In this paper we describe the measurement of the intensity density for $l = 1$ which is calculated by the average $I \cos \theta$.

2. DATA ANALYSIS

The data have been accumulated with the HERMES forward spectrometer [9] during the running period 1996-2000 of HERA. The 27.6 GeV positron beam was scattered off hydrogen and deuterium targets, respectively. Events have been selected with one positron track and two oppositely charged hadron tracks ($E_h > 1$ GeV) without additional neutral clusters in the calorimeter. The exclusivity of these events was ensured by imposing a further cut on the inelasticity $\Delta E = \frac{M_y^2}{M_x^2}$, where $M_y$ is the invariant mass of the undetected system and $M_x$ is the proton mass. As explained above, to enhance the isoscalar production and consequently the interference between the isovector and isoscalar channel, it was also required that $x_{Bj} > 0$. Moreover, in order to enter the hard regime of the process, constraints on $Q^2$ ($Q^2 > 1$ GeV$^2$) and $W$ ($W > 2$ GeV) were imposed, where $W$ is the invariant mass of the virtual-photon nucleon system.

The most important source of background to the exclusive channel comes from fragmentation of partons in semi-inclusive deep inelastic scattering (DIS) at low $\Delta E$. Due to the instrumental resolution and smearing, those events may contaminate the exclusive sample. The shape of the DIS background is well reproduced by a Monte Carlo simulation (MC). It is based on the LEPTO generator using the LUND model and the detector response was simulated by a GEANT-based Monte Carlo code. MC data were normalized to experimental data at $\Delta E > 2$ GeV and then subtracted. In order to illustrate our procedure, in Fig. 3 both the un-subtracted (left panel) and full subtracted (right panel) $\pi^+\pi^-$ data are shown as a function of the inelasticity $\Delta E$. Here only data within the $\pi^+\pi^-$ invariant mass window $0 < m_{\pi\pi} < 1$ GeV, around the $\rho^0$ mass, are shown. Exclusive events were then selected for $\Delta E < 0.625$ GeV to maximize the ratio of the exclusive signal over the background ($S_g - B_g$) and minimize its relative statistical error. For these events the intensity density was calculated in 10 bins of $m_{\pi\pi}$. The intensity density of the background, $I \cos \theta |_{B_g}$, was evaluated using data for $\Delta E > 2$ GeV, assuming its $\Delta E$ independence. This assumption was tested checking the stability of $I \cos \theta |_{B_g}$ in different $\Delta E$ bins. In every bin of $m_{\pi\pi}$, the value of $I \cos \theta |_{B_g}$, weighted by the ratio $S_g / B_g$ for the chosen $\Delta E$ cut, was subtracted. The background corrections range between $10-70\%$ in the various bins.

3. RESULTS

In Fig. 3 the preliminary HERMES results on the $m_{\pi\pi}$-dependence of the intensity density $I \cos \theta$ are shown, for the proton in the left panel and for the deuteron in the right one.
FIGURE 2. Left panel: DIS MC (shaded) normalized to HERMES data (crosses) at $\Delta E > 2$ GeV. Right panel: the exclusive $\pi^+\pi^-$ channel obtained by subtracting the DIS-MC spectrum from the experimental one. In both panels only the $\rho^0$ invariant mass window is considered.

The distributions show a clear angular asymmetry whose size changes with $m_{\pi\pi}$. At low $m_{\pi\pi}$ ($m_{\pi\pi} < 0.6$ GeV) the asymmetry may be due to an interference between the lower tail of the $\rho^0$ meson and the non-resonant $\pi^+\pi^- S$-wave production ($I = 1$ and $I = 0$ interference). This interference is present over the entire invariant mass region considered. At large $m_{\pi\pi}$ ($m_{\pi\pi} > 1.0$ GeV), additionally, an interference between the upper tail of the $\rho^0$ meson and the $f$-type mesons arises and is superimposed. In particular, the possible change of sign of the asymmetry at $m_{\pi\pi} = 1.3$ GeV may be understood as being caused by the interference of the broad $\rho^0$ tail and the $f_2$ resonance ($1.270$ GeV). Note that no similar behavior is seen at the narrow $f_0$ resonance ($0.980$ GeV), possibly due to the experimental resolution.

In Fig. 3 the $x_{Bj}$ dependence of the intensity density $h\cos\theta$ is shown for the proton within

FIGURE 3. $m_{\pi\pi}$-dependence of the intensity density $h\cos\theta$ for the proton (left panel) and the deuteron (right panel). Shaded areas in both panels represent the systematic uncertainty.
the above defined $\rho^0$ window. The size of the $\langle \cos \theta \rangle$ asymmetry increases with $x_{Bj}$. This experimental finding is in agreement with theoretical expectations according to which at increasing $x_{Bj}$ the $\pi^+\pi^-$ production becomes increasingly dominated by $q\bar{q}$ exchange, leading to a sizable admixture of isoscalar and isovector pion pairs. As explained above this leads to an enhancement of the interference term.

The systematic uncertainties have been evaluated considering all hadrons as pions, using different exclusive cuts and applying various procedures for the normalization of the MC generated background to the data. The main contribution has been found to originate from using different exclusive cuts. Using the diffractive DIPSI MC generator \cite{10}, effects due to the acceptance were found to be negligible. Radiative corrections were shown in \cite{11} to be smaller than 1\% in the H1 and ZEUS kinematics. At larger $x_{Bj}$, where the HERMES analysis is performed, they are even smaller, and for that reason have been neglected.

The comparison with the theoretical predictions available so far is promising. In the left (right) panel of Fig. 5 the experimental dependence of the intensity density $\langle \cos \theta \rangle$ on $m_{\pi\pi}(x_{Bj})$ for

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig4}
\caption{$x_{Bj}$-dependence of the intensity density $\langle \cos \theta \rangle$ in the $\rho^0$ invariant mass window for the proton. The shaded area represents the systematic uncertainty.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig5}
\caption{The experimental $m_{\pi\pi}$-dependence (left panel) and $x_{Bj}$-dependence (right panel) of the intensity density $\langle \cos \theta \rangle$ for the proton are compared with theoretical predictions in \cite{2,3}. Triangles (stars) show the predictions with the gluon GPD neglected \cite{2} (included \cite{3}). In the left panel, Triangles have been slightly shifted for a better visibility.}
\end{figure}
the proton is compared with predictions performed at leading twist [2, 3]. The shape of the theoretical distribution is nicely reproducing the data, in particular at the $f_2$ meson mass where the asymmetry changes sign. The reasonable agreement of the leading twist predictions with data may be understood as to arise from the cancellation of higher twist effects in this kind of asymmetry [12].

4. CONCLUSIONS

The $l = 1$ intensity density in $\pi^+ \pi^-$ hard exclusive electroproduction was measured for the first time, for both proton and deuteron at $x_{Bj} > 0$. The quantity $\langle \cos \theta \rangle$ is sensitive to the interference between the isoscalar channel ($I = 0$) and the isovector channel ($I = 1$). The absolute value of the asymmetry measured in the $l = 1$ intensity density $\langle \cos \theta \rangle$ shows a minimum at $m_{\pi\pi} = m_{\rho}$. At smaller invariant mass the asymmetry may be interpreted as originating from the interference of the $\rho^0$ lower tail with the non-resonant $\pi^+ \pi^-$ production ($S$-wave), and at larger invariant mass from the interference of the $\rho^0$ upper tail ($P$-wave) with $\pi^+ \pi^-$ production from the $f_2$ ($D$-wave). The interference signal in the $\rho^0$ invariant mass window was shown to increase in size with $x_{Bj}$. This behavior may be understood as to arise from the increased dominance of $q\bar{q}$ exchange at larger values of $x_{Bj}$, which leads to a sizable admixture of isoscalar and isovector pion pairs.

This is the first evidence of an $I = 0$ admixture in $\pi^+ \pi^-$ exclusive electroproduction. This fact by itself is interesting in view of the importance of the scalar meson sector.

In the GPD framework, theoretical predictions are available with and without inclusion of the GPD describing the two-gluon exchange. Both predictions appear to be consistent with the data. Therefore these results on exclusive $\pi^+ \pi^-$ production, together with results from different exclusive channels (e.g. Deeply Virtual Compton Scattering [13], exclusive $\pi^+ \pi^-$ production [14]) may lead to a better modeling of GPDs.

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