The Quark-Parton Model and Low-Energy Factorization Studies in Semi-Inclusive Pion Production

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Abstract. A large set of $\pi^{\pm}$ electroproduction cross sections from proton, deuterium and aluminum targets have been measured in Hall C. The data cover the range $0.2 < x < 0.6$, $2 < Q^2 < 4$ (GeV/c)^2, and $0.3 < z < 1$, with transverse momenta $P_t < 0.45$ GeV/c, and span the low energy residual-mass region. The cross section data have been used to construct a variety of ratios, in terms of favored to unfavored fragmentation functions, charged pion ratios and deuteron-hydrogen. The x, z and P_t^2 dependencies of the cross sections and their ratios (for $W^2 > 4$ GeV^2 and $z < 0.7$) show the features of factorization in a sequential electron-quark scattering and quark-pion fragmentation process. We find the azimuthal angular dependencies to be small. We find the intrinsic transverse momenta of the u quark to be slightly larger than for d quark, while the transverse momentum width of the favored and unfavored fragmentation functions is about the same, and are larger than the quark widths.

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INTRODUCTION

In this report, we will concentrate on the low-energy domain of semi-inclusive electron scattering. Our focus will be on the process where a quark fragments into a pion, which carries away a large fraction of the exchanged virtual photon's energy.

In the $eN \rightarrow e\pi^{\pm}X$ reaction, an electron with four-momentum $(E,\vec{k})$ scatters from a nucleon with mass M, resulting in a scattered electron with four-momentum $(E',\vec{k}')$, exchanging a virtual photon with four-momentum $q = (\nu,\vec{q})$ with a quark. A meson with four momentum $(E_\pi,\vec{P}_\pi)$, and transverse momentum P_t is produced. We define the four-momentum transfer squared as $Q^2 = -q^2$ and Bjorken x as $x = Q^2/2M\nu$. The fraction of the virtual photon energy taken away by the meson is $z = E_\pi/\nu$. If we neglect the pion mass, and if the meson is collinear with the $\vec{q}$ and $Q^2/\nu^2 \ll 1$, we can present the square of mass of the undetected residual system as $W'^2 = M^2 + Q^2(1-z)(\frac{1}{x}-1)$. Note, in the inclusive case, the square of the invariant mass is $W^2 = M^2 + Q^2(\frac{1}{x}-1)$.

At high energies the cross section factorizes into the product of the virtual photon–quark interaction and the subsequent quark hadronization. A consequence of factorization is that the fragmentation function is independent of x, and the parton distribution function independent of z. At low energies, it is not obvious that the factorization holds.

The quark-hadron duality has been predicted [1], and verified [2] for high-energy meson electroproduction. While the phenomenon of duality in inclusive electron scattering is well-established, duality in the semi-inclusive meson electroproduction was not tested before this experiment. To investigate the existence of quark-hadron duality and its relation to low-energy factorization in semi-inclusive $\pi^{\pm}$ electroproduction was one of the goals of the E00-108 experiment.

EXPERIMENT

The experiment E00-108 [3] ran in 2003 in Hall C at JLab. Incident electrons, with energy of 5.479 GeV and currents $20-60\ \mu A$, were scattered from 4-cm-long liquid hydrogen or deuterium targets and detected in the SOS spectrometer. The electroproduced pions were detected in the HMS spectrometer. The experiment consisted of three parts: i) at a fixed electron kinematics of (x, Q^2) = (0.32, 2.30 (GeV/c)^2), z was varied from 0.3 to 1 by changing the HMS momentum from 1.3 to 4.1 GeV/c, with nearly uniform coverage in the pion azimuthal angle, ϕ, around the $\vec{q}$ direction, but at a $\langle P_t \rangle \approx$0.05 GeV/$c$ (z-scan); ii) for $z = 0.55$, x was varied from 0.2 to 0.6, with a corresponding variation in Q^2 from 1.5 to 4.6 (GeV/c)^2, by changing the SOS angle, keeping the pion centered on the $\vec{q}$ direction (x-scan); iii) for (x, Q^2) = (0.32, 2.30 (GeV/c)^2), $z \approx$0.55, P_t was scanned from 0 to 0.4 GeV/c by increasing the HMS angle (with $\langle \phi \rangle \approx 180^o$) ($P_t$-scan).

EXPERIMENTAL RESULTS

Many of the results are described in detail in [2, 4, 5]. We observed for the first time the quark-hadron duality phenomenon and the onset of low-energy factorization in semi-inclusive pion electroproduction. We compared the measured ^{1,2}H(e,e$'\pi^{\pm}$)X cross sections as a function of z (at x = 0.32) with the parton model calculation assuming CTEQ5M parton distribution functions [6] and the parametrized fragmentation functions of Binnewies, Kniehl and Kramer [7]. We found good agreement between data and model for $z < 0.65$. We constructed several ratios of cross sections off proton and deuteron targets, and found the ratio of fragmentation functions D^-/D^+ to closely resemble that of high-energy reactions. We studied the cross sections as a function of the P_t^2 in the context of a simple model, allowing separate widths for up (μ_u) and down (μ_d) quarks, and for favored (μ_+) and unfavored (μ_-) fragmentation functions, and assuming Gaussian distributions. We fit the P_t-dependence of the $\pi^{\pm}$ cross sections for hydrogen and deuterium for the four widths, and the D^-/D^+ and d/u ratios. We find the ratio $d/u = 0.39 \pm 0.03$, and $D^-/D^+ = 0.43 \pm 0.01$, in good agreement with the high energy data, and the width squared for u quarks $\mu_u^2 = 0.07 \pm 0.03$ (GeV/c)^2. But for the d-quark width squared the fit gives value consistent with zero ($\mu_d^2 = -0.01 \pm 0.05$ (GeV/c)^2), and nearly similar values for the fragmentation widths ($\mu_+^2 = 0.18 \pm 0.02$ (GeV/c)^2 and $\mu_-^2 = 0.14 \pm 0.02$ (GeV/c)^2).

At z = 0.55, we have studied the x- and Q^2- dependencies of the $^{1,2}H(e, e'\pi^{\pm})$X cross sections. We found good agreement between the data and model, as shown in Fig. 1 (left panel) for the x-dependence of the π^+ cross sections at Q^2_{set} = 3.8 (GeV/c)^2. To study the

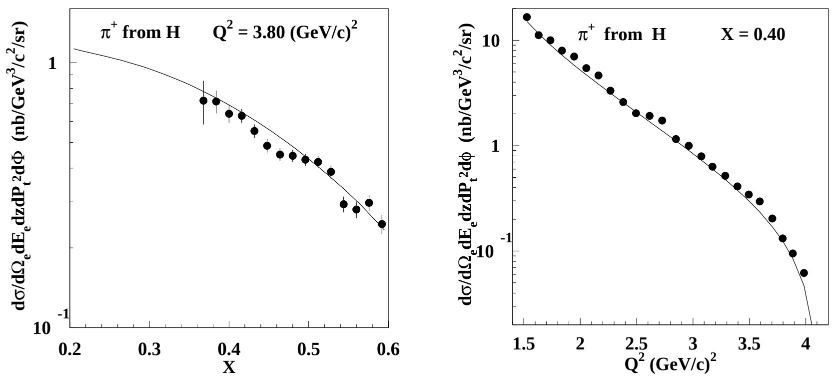

FIGURE 1. The ^{1}H(e,e$'\pi^+$)X cross section. Left: As a function of x at $z = 0.55$, Q^2_{set} = 3.80 (GeV/c)^2. Right: As a function of Q^2 at x = 0.40, z = 0.55. The curves are the quark-parton model calculations.

Q^2-dependence of the cross sections, we bin centered in x to a common x = 0.40. The ${}^1H(e,e'\pi^+)$X cross section versus Q^2 is shown in the right panel of Fig. 1. The parton model calculations describe our data remarkably well.

In Fig. 2 the π^+/π^- ratios are shown as functions of z (at $x = 0.32$), x and Q^2 (at $z =$ 0.55). The solid and open triangles are Cornell data [8] at $(x,\ Q^2)$ = (0.24, 2.0 (GeV/c)^2) and (0.50, 4.0 (GeV/c)^2), respectively. Stars represent HERMES data [9] at average values of $\langle Q^2\rangle$=2.5 (GeV/c)^2, $\langle W^2\rangle$=28.6 GeV^2, $\langle \nu\rangle$=16.1 GeV and $\langle x\rangle$=0.082. The solid line is the quark-parton model calculation. The π^+/π^- ratio from the proton is larger than those reported by HERMES, but agrees well with the Cornell data, and is consistent to the rise in z as expected from the quark-parton model calculation up to $z \approx 0.6$. For $0.65 < z <$0.85, the ratio decreases because the $\pi^-\triangle^{++}$ cross section is larger than the $\pi^+\triangle^o$ one. The sharp rise of the ratio at $z > 0.85$ is due to exclusive π^+ production. Similarly the deuteron also reproduces the expected rise from the quark-parton model calculation. At $z > 0.7$ we see again effects rising from the $N-\Delta$ transition.

In the central panel of Fig. 2 we show the π^+/π^- ratio versus x for proton (top) and deuterium (bottom) targets. Solid and open triangles represent data from Cornell [8] at $(x,\ Q^2)$ = (0.24, 2.0 (GeV/c)^2), and (0.50, 4.0 (GeV/c)^2). Our π^+/π^- ratios is in good agreement with the Cornell data and with the quark-parton model prediction.

The π^+/π^- ratio versus Q^2 (at z = 0.55) shown in right panel of Fig. 2, agrees well with the quark-parton model expectations.

If factorization, isospin symmetry and charge conjugation holds, the $\pi^\pm$ cross sections on the proton and deuteron can be used to extract the d_v/u_v ratio of valence quarks ($u_v = u - \bar{u}$, and $d_v = d - \bar{d}$). This ratio is shown in Fig. 3, as a function of x (at z=0.55), z (at $x = 0.32$) and P_t^2 (at $x = 0.32$ and $z = 0.55$). Our data are in good agreement with WA21/25 [10] and EMC [11] results, but below the HERMES data [12]. The ratio d_v/u_v may contain z-dependent factors, if the symmetry breaks down. One can witness in Fig. 3 (central panel) a sharp increase of the d_v/u_v ratio at $z > 0.7$ where the $\triangle$ transition comes into play. There is no apparent P_t -dependence of the ratios as can be seen in the right panel, although future higher-precision data are required to rule out any dependence.

We believe our work will provide a fruitful basis for future studies of the quark-parton model and more sophisticated model calculations at relatively low energies.

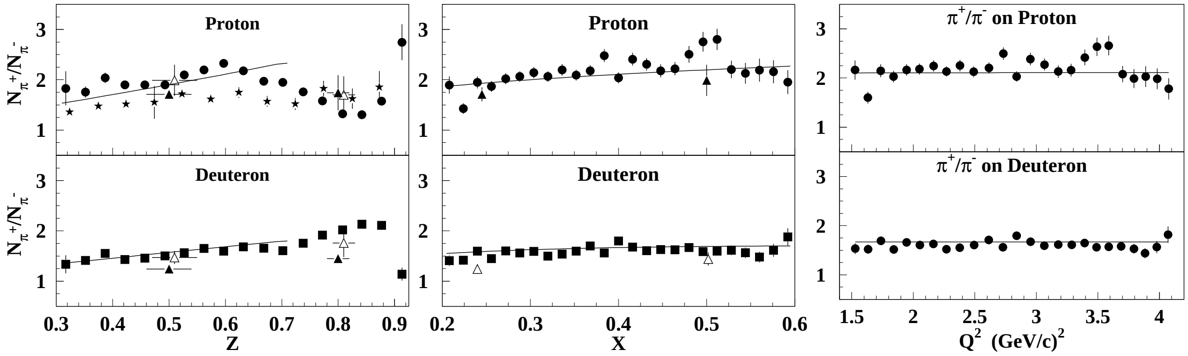

FIGURE 2. The ratio π^+/π^- for proton (top) and deuteron (bottom) targets. Left: π^+/π^- as a function of z, at $x = 0.32$. Solid and open triangles are Cornell data [8], and stars are HERMES data [9]. Center: Ratio π^+/π^- as a function of x at $z = 0.55$. Solid and open triangles are Cornell data [8]. Right: The ratio π^+/π^- as a function of Q^2 for x = 0.4 and z = 0.55. The lines are the quark-parton model expectations.

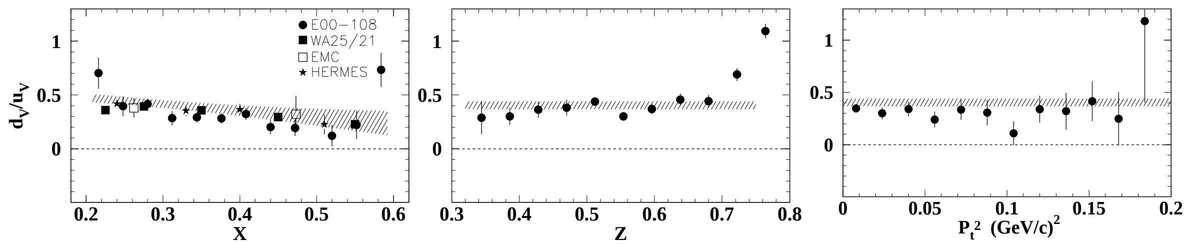

FIGURE 3. Left: The ratio of valence quarks d_v/u_v as a function of x at z=0.55. Solid and open squares represent data from WA-21/25 [10] and EMC [11]. Solid triangle symbols are HERMES data [12]. Center: The d_v/u_v as a function of z at x=0.32. Right: The ratio d_v/u_v as a function of P_t^2 at x=0.32 and z=0.55. The band is a quark-parton model expectation using CTEQ parton distribution function parameterizations [6].

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