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Electroproduction of Single Pions with Large Transverse Momenta*

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We report measurements of the electroproduction reaction $ep \to e\pi^+n$ for pions produced between 60 and 90° in the virtual-photon–proton center-of-mass system. The cross section is studied as a function of the center-of-mass energy, W, and the square of the virtual-photon mass, $-Q^2$, in the region 1.2 GeV $\leq W \leq$ 3.0 GeV, 1.2 GeV^2 $\leq Q^2 \leq$ 4.4 GeV^2. The data show a strong W dependence in accord with simple quark-model predictions but exhibit a Q^2 dependence which is difficult to explain in the context of such a model.

In the past several years, there have been extensive measurements of the electroproduction reaction

$$ep \to e\pi^+n \tag{1}$$

with the pion produced along the direction of the virtual photon.[1,2] These data are interpreted within the context of the electric-Born-term model and are used to determine the pion form factor.[2,3] The main features of the data are a strong dependence on the square of the virtual-photon mass, $-Q^2$, and a relatively weak dependence on the center-of-mass energy, W. Quite a different behavior is expected for pions emitted at large angles with respect to the virtual-photon direction. In this region of large momentum transfers, the parton structure of the hadrons should reveal itself and dominate the cross section. One particular model, the parton-interchange model,[4] predicts for any reaction $a+b\to c+d$ a cross section of the form

$$d\sigma/d\Omega_c \propto (W^{2n-6})^{-1}f(\theta) \tag{2}$$

for large center-of-mass energies W and center-of-mass angles θ near 90°. Here n is simply the sum of the number of elementary fields contained in particles a, b, c, and d. If Reaction (1) is viewed in terms of the equivalent virtual-photon reaction

$$\gamma_v p \to \pi^+ n \tag{3}$$

and the standard quark assignments are used for the participants, this model predicts a cross section that falls as W^{-12}. This model does not make a definitive statement concerning the Q^2 dependence of the cross section. It is expected, however, that the Q^2 dependence would be weak and characteristic of the quark form factor rather than hadronic form factors.

This paper reports the first measurments of a two-body virtual-photon reaction at very large momentum transfer. This work extends previous measurements[2] of Reaction (1) into the region near 90° in the virtual-photon–proton center-of-mass system. The measurements were carried out at the Cornell University Wilson Synchrotron Laboratory.

Electroproduction can be treated as photoproduction by a virtual photon, whose mass squared $-Q^2$, energy ν, direction, and polarization parameter ϵ are tagged by the detected electron.[1] The cross section for Reaction (1) is written

$$d^3\sigma/d\Omega_e\, dE_e\, d\Omega_\pi = \Gamma\, d\sigma/d\Omega_\pi,$$

where Γ is the "flux" of virtual photons. $d\sigma/d\Omega_\pi$ is the cross section for the production of the π^+n final state by a virtual photon and is a function of the virtual-photon variables Q^2, ν (or W), and ϵ, and the polar angle θ and azimuth φ describing the detected π^+ in the virtual-photon-proton c.m. system.

The two magnetic spectrometers shown in Fig. 1 were used to obtain data in the region of 1.2 GeV$^2 \leq Q^2 \leq 4.4$ GeV^2, 1.2 GeV $\leq W \leq 3.0$ GeV, $55° \leq \theta \leq 95°$, $100° \leq \varphi \leq 150°$, and $0.85 \leq \epsilon \leq 0.95$. A shower counter served to identify the electrons. Pions were identified by a threshold gas Cherenkov counter when their momenta were greater than 1.5 GeV/c and by their time of flight at lower momenta. The data have been corrected for random coincidences (~1%), counter and spark chamber dead time (~7%), target wall background (~5%), absorption in the counters (~5%), and pion decay losses (~3%). In addition, we applied a radiative correction of ~40% following a prescription of Bartl and Urban.[5] The radiative correction varied by less than 7% over all the data points in the experiment. The uncertainties shown are statistical only and do not include a possible systematic error which, excluding the radiative correction, is estimated to be less than 7%. The systematic error in the radiative correction is estimated to be less than 1%.

Figure 2 shows the virtual-photoproduction cross section as a function of angle for fixed W and Q^2. The cross section is sharply peaked in the forward direction[2] and becomes relatively flat near 90°.

Figure 3 displays the W dependence at $Q^2 = 1.2$ GeV^2 for four different angles. The solid curves represent the best fits of the form

$$d\sigma/d\Omega_\pi = a_1 W^{a_3}/(Q^2)^{a_2}. \qquad (4)$$

The fits include all Q^2 between 1.2 and 4.4 GeV^2 and all W between 2.0 and 3.0 GeV. The coefficients of the fit for each angular region are given in Table I. The W dependence becomes weaker at smaller angles as it must since in the forward direction the cross section falls as W^{-2}. In addition to the fit shown, the 90° data were also fitted over the region $W > 1.7$ GeV. The result of that fit is that the cross section falls as $W^{-12.6\pm0.40}$. We have seen no evidence for this exponent changing with Q^2. The W dependence agrees with the

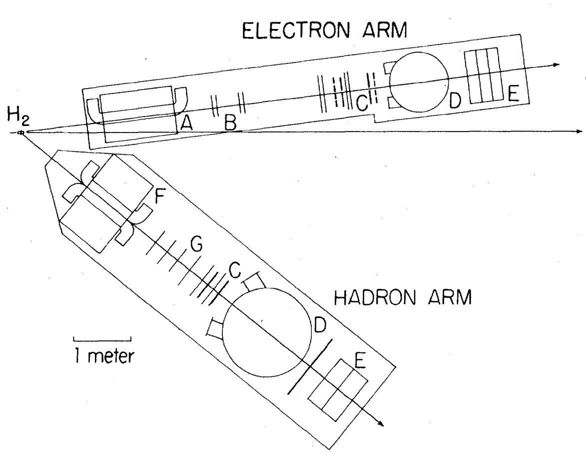

FIG. 1. A schematic view of the apparatus. A and F: bending magnets; B: multiwire proportional counters; C: scintillation counters; D: Freon Cherenkov counters; E: lead-Lucite shower counters; G: wire spark chambers; H_2: liquid-hydrogen target.

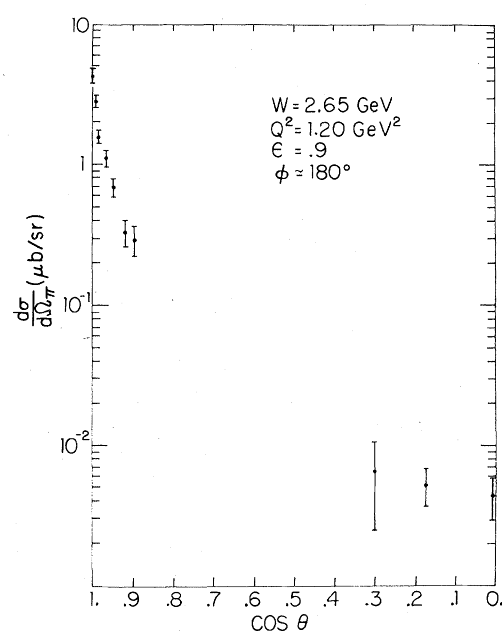

FIG. 2. The angular distribution for the reaction $\gamma_v p \to \pi^+ n$ at fixed W, Q^2, ϵ, and φ. The small-angle points are from Ref. 2.

TABLE I. The parameters obtained from a fit of the form (4) for four values of θ. The second and third columns give the approximate range of values of W and Q^2 for which data exist. The units of a_1 are such that for W in GeV and Q^2 in GeV^2, $d\sigma/d\Omega_\pi$ is in μb/sr.

θ (deg)	W (GeV)	Q^2 (GeV^2)	a_1	a_2	a_3
55–65	2.0–2.5	1.2–2.0	88 ± 81	1.03 ± 0.33	− 7.46 ± 1.06
65–75	2.0–2.7	1.2–2.0	502 ± 307	0.84 ± 0.21	− 10.43 ± 0.71
75–85	2.0–3.0	1.2–2.8	813 ± 345	1.08 ± 0.13	− 11.62 ± 0.53
85–95	2.0–3.0	1.2–3.6	1532 ± 833	1.46 ± 0.16	− 12.87 ± 0.66

parton-interchange-model prediction[4] of W^{-12} and with photoproduction measurements.[6] It is surprising, however, that this simple dependence extends to values of W less than 2 GeV.

In Fig. 4 we display the Q^2 dependence of the cross section at 90° for two values of W. At each Q^2 the cross section was obtained by projecting all the data in two W bins (2.15 ± 0.25 and 2.65 ± 0.25 GeV) to the central W values by use of the observed W dependence. The photoproduction point at 90° was obtained by projecting the data of Ref. 6 from $W = 2.90$ GeV to $W = 2.65$ GeV by use of the W dependence observed in that experiment. Also shown is the Q^2 dependence at 0°.[2,7] Apart from an overall scale factor, the data at 0 and 90° are remarkably similar. The falloff at larger Q^2 which is essentially proportional to the square of the pion form factor is quite different from the prediction of the simple quark model in which the behavior at 90° is dominated by the interaction of the virtual photon with a single quark. The initial rise of the forward cross section with Q^2 is due to a large contribution by

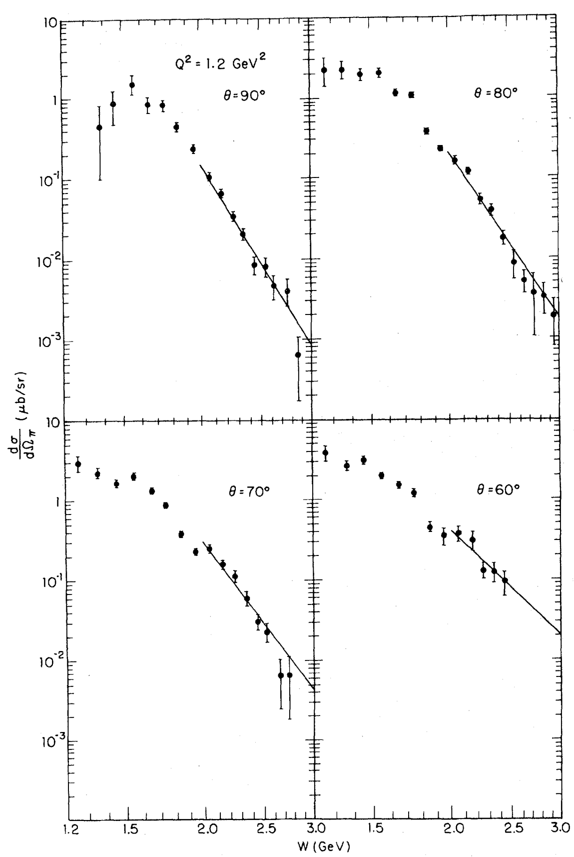

FIG. 3. The W dependence of Reaction (3) for fixed Q^2 at four different angles. The solid curves are the fit (4).

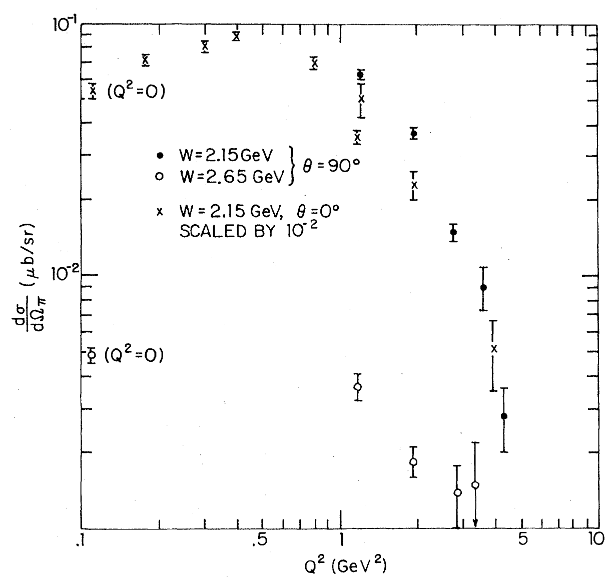

FIG. 4. The projected Q^2 dependence of Reaction (3) for two values of W and $\theta = 90°$. Also shown in the dependence at $W = 2.15$ GeV and $\theta = 0°$ (Ref. 2). The photoproduction points are from Refs. 6 (90°) and 7 (0°).

longitudinal photons via the one-pion-exchange diagram. The data of this experiment taken in conjunction with the photoproduction 90° cross section are suggestive of a similar contribution at large momentum transfer. This again can be contrasted to the simple quark model which predicts that only transverse photons will contribute. The data can be understood simply in terms of a vector-dominance-like model in which the Q^2 dependence is given by the ρ propagator and the W dependence is the same as that observed in $\pi p \to \pi p$ elastic scattering.

In conclusion, we have observed the W dependence of Reaction (3) at 90° to be in agreement with the prediction of the parton-interchange model. However, it seems difficult to explain the observed Q^2 dependence within the framework of this model.

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Measurement of Neutrino and Antineutrino Total Cross Sections at High Energy*

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Charged-current ν and $\bar{\nu}$ data are reported from the first application at Fermilab of a narrow-band neutrino beam for the measurement of normalized cross sections. Cross sections of about 20% accuracy were measured with a 120-GeV secondary hadron beam for ν ($\bar{\nu}$) originating from π decay ($\langle E_\nu \rangle = 38$ GeV) and K decay ($\langle E_\nu \rangle = 105$ GeV). The ν and $\bar{\nu}$ fluxes were determined by directly measuring the hadron flux and the $\pi/K/p$ ratios for the hadron beam.

The usual local current-current weak-interaction theory predicts that the neutrino-lepton cross section at high energy rises linearly with laboratory energy. If, in addition, the deep-inelastic structure functions scale in the dimensionless scaling variable x, the neutrino-nucleon cross section must rise linearly with laboratory energy as well.[1] The behavior of the total neutrino (antineutrino) charged-current cross section σ_ν ($\sigma_{\bar{\nu}}$) on nucleons,

$$\nu_\mu \ (\bar{\nu}_\mu) + N \to \mu^- \ (\mu^+) + \text{hadrons},$$

therefore provides simultaneously a directly interpretable check of both weak-interaction theory and scaling.

Neutrino and antineutrino cross sections[2] previously measured at low energies ($E_\nu \lesssim 8$ GeV) are consistent with a linear rise in energy. The best-fit slopes are $\alpha_\nu = 0.74 \pm 0.03$ and $\alpha_{\bar{\nu}} = 0.28 \pm 0.01$, where all α's are in units of 10^{-38} cm^2/GeV. We describe here a measurement of σ_ν and $\sigma_{\bar{\nu}}$ at higher energy in which the neutrino flux has been measured directly in the same experiment. (Preliminary results from this experiment have been presented earlier.[3])

This is the first application of a narrow-band