and Photon Interactions at High Energies, Stanford, California, 1975, edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975).

[11]Our choice for the value of a is guided by the recent results of a muon experiment at Fermilab. See W. A. Loomis *et al.* Phys. Rev. Lett. 35, 1483 (1975); H. L. Anderson *et al.*, Phys. Rev. Lett. 36, 1422 (1976). Our variable z and the variable x' used in these two papers are essentially the same for not too small values of z.

[12]Our choice for b is guided by the experimental results of Ref. 10, and reflects the thinking that the transverse size of the virtual photon shrinks with Q^2. See, e.g., J. D. Bjorken, in *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Ithaca, New York, 1971,* edited by N. B. Mistry (Cornell University, Ithaca, N. Y., 1971).

[13]For lack of better candidate, we have adopted for the semileptonic decay distribution of a charmed hadron the same lepton spectrum as in the decay of $c \to s + \mu^+ + \nu$ according to the charm scheme. However, we use the physical masses 1.86 GeV and M_K for the c and s quarks, respectively.

[14]As a first approximation, we assume the two charmed hadrons to be dynamically uncorrelated in production.

[15]For a discussion of the interpretation of scaling violation, see W. K. Tung, Phys. Rev. Lett. 30, 1087 (1975).

Comparison of π^+ and π^- Electroproduction at 0° and 90° Center-of-Mass Angles*

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We report measurements of the ratio of positively charged to negatively charged pions electroproduced at 0° and 90° in the virtual photon-nucleon center-of-mass system. The π^+/π^- ratio is studied as a function of W, Q^2, ω, x_T, and x in the range 2.1 GeV $\leq W \leq$ 3.2 GeV and 1.2 GeV$^2 \leq Q^2 \leq$ 9.5 GeV^2.

The Feynman parton-quark model[1] predicts that for pions produced along the direction of the virtual photon in virtual-photon–proton collisions the ratio of the number of positively charged to negatively charged pions should be a function only of ω as W and Q^2 vary, and that it should increase as $1/\omega$ increases. Available data for forward produced pions are consistent with either an ω or W dependence but are not of sufficient quality or range to make a clear choice.[2,3] Although there are no explicit predictions for the charge ratio at 90° in the virtual-photon–nucleon center-of-mass system, it is presumably given by the constituent-interchange model.[4] It is important to determine experimentally the π^+/π^- ratio over a wide kinematic range to test these models further and to compare the behavior at 90° with that at 0°.

We report here new measurements of the π^+/π^- ratio for the electroproduction reaction

$$e + p \to e + \pi^{\pm} + \text{anything} \tag{1}$$

for pions produced at 0° and 90° in the virtual-photon–proton center-of-mass system, and for the reaction

$$e + n \to e + \pi^{\pm} + \text{anything} \tag{2}$$

for pions produced at 0°. Reactions (1) and (2) are analyzed in terms of the virtual photoproduction reaction[5]

$$\gamma_v + N \to \pi^{\pm} + \text{anything}. \tag{3}$$

The square $-Q^2$ of the mass, energy ν, direction, and polarization parameter ϵ of the virtual photon are tagged by the scattered electron. The π^+/π^- ratio is studied as a function of W (the total energy of the virtual-photon–target-nucleon system), Q^2, $\omega = 2M\nu/Q^2$, and the center-of-mass variables $x_T = p_T/p_{\max}^*$ and $x = p_{\parallel}^*/p_{\max}^*$. Here p_T and $p_{\parallel}^*$ are the components of the pion momentum transverse and parallel to the virtual photon direction and $p_{\max}^*$ is the maximum momentum kinematically allowed for the π^+ reaction.

Data were taken with the two-arm spectrometer system described earlier.[6] Shower counters were used to identify electrons. Pions were identified by a combination of threshold Cherenkov counters and time of flight. The uncertainties in the figures are statistical only. Systematic corrections to the π^+/π^- ratios are estimated to be less than 1%.

Figure 1 shows the x_T dependence of the π^+/π^- ratio for the eight (W, Q^2) points taken for pions produced near 90° in the virtual-photon–proton center-of-mass system with a hydrogen target.

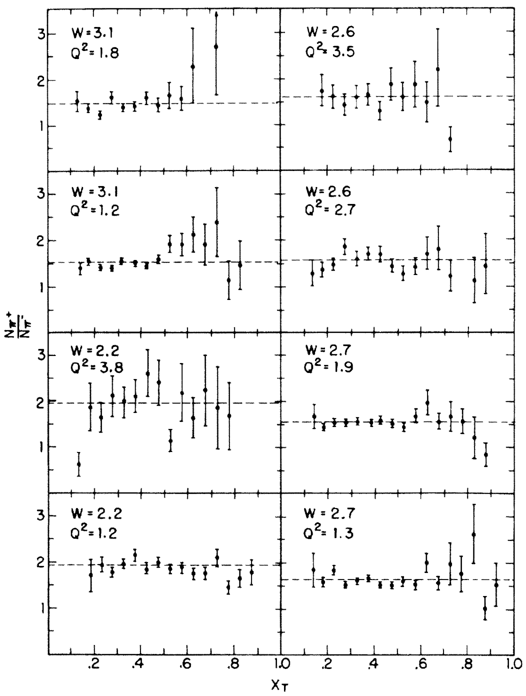

FIG. 1. Plots versus x_T of the π^+/π^- ratio for pions produced near 90° in the virtual-photon–target-proton center-of-mass system.

For these data $-0.05<x<0.05$, $0.80<\epsilon<0.95$, and $-140°<\varphi<-160°$, where φ is the angle between the electron scattering plane and the virtual-photon–electroproduced-hadron plane. The data show that the ratio is independent of x_T over the entire range. We have calculated the final π^+/π^- ratio for each (W, Q^2) by integrating over the x_T distributions.

The integrated π^+/π^- ratios for $-0.05<x<0.05$ are displayed in Fig. 2 both as a function of $1/\omega$ and as a function of W. The data are clearly described more precisely as a function only of W than as a function only of ω. The observed behavior is that expected from thermodynamic models.[7] For electroproduction the average charge multiplicity is known to vary as $\ln W$ and to be independent of Q^2.[8-11] Since the observed reaction starts with a proton in the initial state, one expects the average π^+/π^- ratio to be larger than 1 for small W and to approach 1 asymptotically as W increases.

Figure 3 shows the variation with x of the π^+/π^- ratio near 0° for a proton target for the five new (W, Q^2) points together with measurements from earlier experiments carried out with a similar setup.[2] For these data $p_T^2<0.02$ GeV^2. At low W the π^+/π^- ratio is a function of x which increases

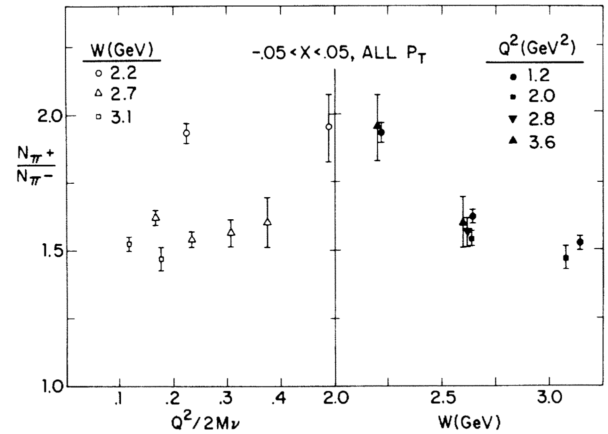

FIG. 2. Plots versus $Q^2/2M\nu$ and W of the π^+/π^- ratio for pions produced near 90° in the virtual-photon–target-proton center-of-mass system.

as x increases. At high W the π^+/π^- ratio is a constant and independent of x. At the largest values of x the π^+/π^- ratio decreases because the cross section for the $\pi^-\Delta^{++}$ channel is larger than that for the $\pi^+\Delta^0$ channel.

Figure 4 shows the π^+/π^- ratio integrated over the region $0.3<x<0.7$ as a function of W and ω for both proton and neutron targets. The data show that for the proton the ratio is better described as a function of ω than as a function of W. The data for the neutron are not sufficiently precise to decide between a function of ω and a function of W. Also shown in Fig. 4 is a parton-model fit to the proton data using the procedure of

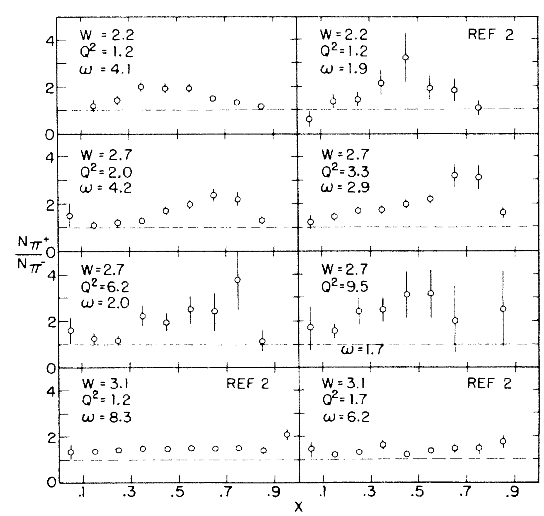

FIG. 3. Plots versus x of the π^+/π^- ratio for pions produced near the direction of the virtual photon in the region $p_T^2<0.02$ GeV^2.

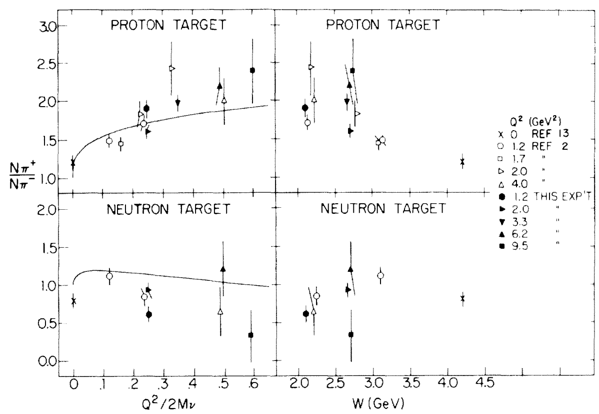

FIG. 4. Plots versus $Q^2/2M\nu$ and ω for the π^+/π^- ratio for both proton and neutron targets. The electroproduction data are for $0.3 < x < 0.7$ and $p_T^2 < 0.02$ GeV^2. The photoproduction data are integrated over all x and all p_T^2.

Dakin and Feldman.[12] For this fit

$$\eta = D_u^{\pi^+}(x)/D_d^{\pi^+}(x) = 2.2 \pm 0.1, \tag{4}$$

where $D_i^h(x)$ is the probability of an i-type quark fragmenting into a hadron of type h carrying a fraction x of the quark's momentum. This fit assumes that η is independent of x. Figure 3 shows that this is true only at the highest energy for the data reported here. The π^+/π^- ratio for the neutron is generally lower than that predicted by the model.

Figure 5 shows the π^+/π^- ratio for the proton determined in this experiment together with the results from other experiments[2,3,13-15] plotted versus ω. We have not included the results from

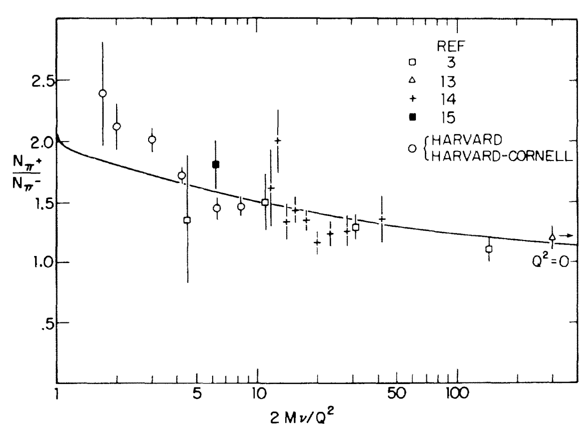

FIG. 5. A plot versus $2M\nu/Q^2$ of the world data for the π^+/π^- ratio. Results from low-energy ($W < 5$ GeV) experiments in which the pions were not identified have not been included.

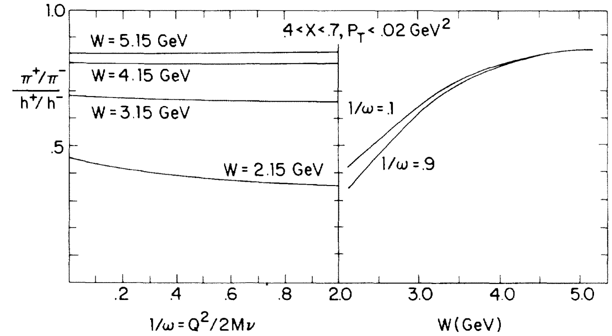

FIG. 6. Plots versus $Q^2/2M\nu$ and W of the ratio $(\pi^+/\pi^-)/(h^+/h^-)$, where h signifies hadrons calculated from the earlier published data of the Harvard University group for inclusive pion, proton, and kaon production.

low-energy experiments ($W < 5$ GeV) in which the pions were not identified.[16,17] The curve shown in Fig. 5 is a fit to the world π^+/π^- data with $\eta = 2.1 \pm 0.1$.

Experiments which do not identify the pion generally give the charge ratio for hadrons h^+/h^-. Figure 6 shows the ratio $(\pi^+/\pi^-)/(h^+/h^-)$ calculated from the measurements by the Harvard University group of the structure functions[2,18,19] for π^+, π^-, K^+, and p. The correction is quite large at low energy but decreases as the energy increases. The application of this correction brings the h^+/h^- measurements[16,17] into reasonable agreement with the π^+/π^- results shown in Fig. 5. From a fit to the measurements available earlier including h^+/h^- data, Dakin and Feldman obtained $\eta = 3.0$.

The world data for $x > 0.3$ are in essential agreement and support the parton-model assertion that the π^+/π^- ratio is a function of ω which increases as $1/\omega$ increases. On the other hand, at 90° the π^+/π^- ratio depends on W rather than ω. An indication of this different behavior between 0° and 90° was reported earlier by the Stanford Linear Accelerator Center–University of California at Santa Cruz muon bubble chamber group.[16]

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Precision Comparison of Inelastic Electron and Positron Scattering from Hydrogen*

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Using 13.5-GeV beams at Stanford Linear Accelerator Center, we have compared electron and positron inelastic scattering over the range $1.2 < |q^2| < 3.3$ (GeV/c)^2, $2 < \nu < 9.5$ GeV for the four-momentum and energy transfers, respectively. We find the ratio of the cross sections to be $e^+/e^- = 1.0027 \pm 0.0035$ (including statistical and systematic effects), with no significant dependence on q^2 or ν. This result has appreciably smaller errors than previous attempts to find two-photon-exchange effects in electron or muon scattering.

Numerous experiments have been performed seeking a difference between lepton and antilepton elastic[1] or inelastic[2] scattering from protons. Such a difference could occur as a result of the interference of one-photon and two-photon exchanges and might be expected to appear at about the 1% ($\sim \alpha$) level. Intermediate-state resonances or parton effects[3] could enhance this, or a type of direct lepton-hadron interaction[4] could also give a significant e^+-e^- difference. While this difference measurement could then be a potentially sensitive probe of the lepton-hadron interaction, it is certainly important for knowing the validity of the one-photon-exchange approximation, on which the whole analysis of lepton-nucleon scattering is based. We have increased considerably the accuracy to which e^+ and e^- scattering have been compared, finding no evidence for any difference to a level of about $\frac{1}{3}$%, integrated over our kinematic range of $1.2 < |q^2| < 3.3$ (GeV/c)^2 and $2 < \nu < 9.5$ GeV for the photon mass and energy, respectively.

It is obviously important in achieving such a result to make the e^+ and e^- beams as much alike as possible. Both the positrons and the electrons were produced by the electron beam in a radiator one third of the way down the Stanford Linear Accelerator Center (SLAC) linac and accelerated to 13.5 GeV in the remaining two thirds of the accelerator. Slits limited the maximum momentum spread of the beam to < 0.4%, and the position of the approximately 4-mm×2-mm beam at the target was set to about 0.5 mm. This random setting uncertainty, which will be discussed among the systematic errors, fixed the beam angle to 0.1 mrad. Interleaved e^+ and e^- data were collected in equal amounts at three beam intensities (3×10^7, 5×10^7, and 7×10^7 e's/pulse) and no rate dependence was found even in the cross sections, making the effect on the e^+/e^- ratio completely negligible. The net beam flux was determined with a secondary-emission quantameter.

The beam interacted in a 12.5-cm liquid hydrogen target, and the scattered positrons or elec-