with other measurements. They are in good agreement and scaling is reasonably well satisfied.

The annihilation model also predicts scaling in the ratio of the π^+- to π^--induced μ-pair production cross sections. The data are shown in Fig. 2(b). The ratio is consistent with being a function of M^2/s only.

In conclusion, we have performed a number of new tests of the Drell-Yan annihilation mechanism. The observed spin alignment of the μ pair and the strong dependence of the cross section on beam-particle species are in striking agreement with the hypothesis that the production proceeds through an electromagnetic quark-antiquark annihilation.

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Determination of the Pion Structure Function from Muon-Pair Production

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Data on muon-pair production by pions are used to determine the momentum distribution for valence quarks in the pion. The shape of a nucleon structure function is also obtained and is compared with a calculation based on existing data.

In the two preceding Letters,[1] we have presented features of high-mass muon-pair production and compared the data with predictions from a quark-antiquark annihilation model. In this Letter, the data are used within the framework of the model to obtain the momentum spectrum of valence quarks in the charged pion.

The general form of the Drell-Yan cross section[2] in terms of the quark distribution functions is given in Ref. 1. There are a number of simplifications in its application to this experiment. For a pion it follows from charge conjugation and isospin invariance that the quark distribution function is the same for both valence quarks. Further, if the kinematic region is restricted to $M > 4\ \mathrm{GeV}/c^2$ ($x_1 > 0.25$), the contribution of sea quarks in the pion is expected to be negligible.[3] Then for pion-nucleon collisions the sum over quark flavors reduces to two terms corresponding to the two valence quarks in the pion. The Drell-Yan cross section for $\pi^- N$ interactions and colored quarks becomes

$$\frac{d^2\sigma}{dM\,dx_\mathrm{F}} = \frac{8\pi\alpha^2}{9M^3(x_1+x_2)}\,x_1\bar{u}^\pi(x_1) \times \left[\tfrac{4}{9}x_2 u^N(x_2) + \tfrac{1}{9}x_2\bar{d}^N(x_2)\right] \qquad (1)$$

or

$$M^4\frac{d^2\sigma}{dx_1\,dx_2} = \frac{4\pi\alpha^2 s}{9}f^\pi(x_1)g^N(x_2), \qquad (2)$$

where $f^\pi(x_1) \equiv x_1\bar{u}^\pi(x_1)$ and $g^N(x_2) \equiv \frac{4}{9}x_2 u^N(x_2) + \frac{1}{9}x^2 \times d^N(x_2)$.

Since $M^2/s = x_1 x_2$, the cross section as a function of x_1 and x_2 is predicted to factor into a function of x_1 times a function of x_2. Equation (2) is used to test the factorization hypothesis and to deduce the functions $f^\pi(x_1)$ and $g^N(x_2)$. To use Eq. (2), data with $4 < M < 8.75\ \mathrm{GeV}/c^2$ and $x_\mathrm{F} > -0.05$ are binned in a rectangular grid of x_1 and x_2. Higher-mass pairs are excluded to avoid possible contributions from unresolved resonances (Υ, Υ'). Figure 1 shows the distribution of events in the x_1-x_2 plane. The range of x_1 ($0.25 < x_1 < 1.0$) is divided into fourteen bins and the range of x_2 ($0.05 < x_2 < 0.28$) divided into nine bins. The 85 populated bins are fitted with the form of Eq. (2), yielding fourteen values of $f^\pi(x_1)$ and nine values of $g^N(x_2)$. We find a χ^2 of 65 for 61 degrees of freedom indicating good agreement with the factorization hypothesis.

Only the normalization of the product $f^\pi(x_1) \times g^N(x_2)$ is measured in this type of experiment. Additional information is required to fix the normalization of the pion structure function. The target-nucleon function $g^N(x_2)$, cannot be normalized directly to data from deep-inelastic lepton-scattering experiments because such experiments measure a different linear combination of quark distribution functions. Several authors[4] have extracted the individual nucleon quark distribution functions using fits to deep-inelastic lepton-scattering data with the q^2 dependence expected from quantum chromodynamics. In addition, a nucleon sea-quark distribution has been determined by Kaplan *et al.*[5] Over the interval $0.05 < x_2 < 0.28$, we normalize $g^N(x_2)$ to $\frac{4}{9}xu^N(x) + \frac{1}{9}x\bar{d}^N(x)$, where the u-valence-quark distribution is taken from Buras and Gaemers[4] with $q^2 = -m^2$, and the u and $\bar{d}$ sea-quark distributions are taken from Ref. 5. In Fig. 2, the normalized nucleon structure function is shown together with the expected form. The agreement in shape is excellent.[6] For comparison, Fig. 2 also shows the expected function if both valence- and sea-quark distributions are taken from Ref. 4. If these curves were used to normalize $g^N(x_2)$ the normalization would be 20% smaller. A comparison of the resulting data points with these shapes would have a χ^2 confidence level of 6%.

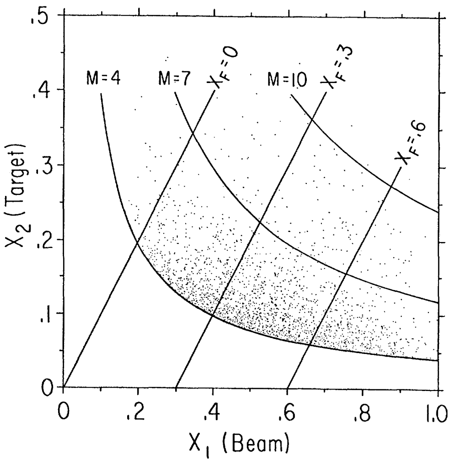

FIG. 1. Distribution of events in the x_1-x_2 plane. Lines of constant x_F ($x_\mathrm{F} = x_1 - x_2$) and M ($x_1 x_2 = M^2/s$) are also shown.

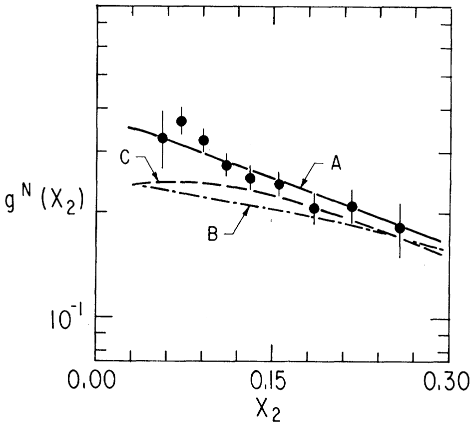

FIG. 2. The nucleon structure function $g^N(x_2) = \frac{4}{9}x_2 \times u^N(x_2) + \frac{1}{9}x_2\bar{d}^N(x_2)$ averaged over protons and neutrons in the C, Cu, and W targets. Curve A is used to normalize the data points and is described in the text. Curve B is from Buras and Gaemers, Ref. 4. Curve C is from Fox, Ref. 4.

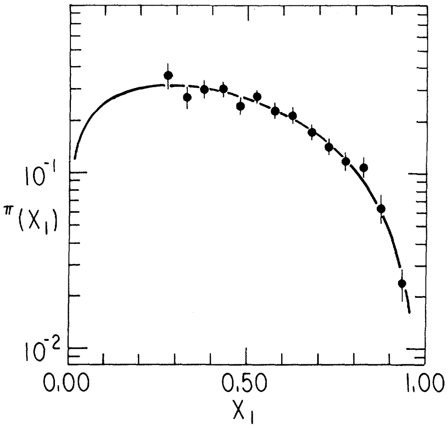

FIG. 3. The pion structure function $f^{\pi}(x_1) = x_1\bar{u}^{\pi^-}(x_1)$.

TABLE II. Nucleon-structure-function fits: χ^2 per degree of freedom (χ^2/DF) for fit to normalization curve of Fig. 2.

	χ^2/DF
$4.0<M<8.75$, all p_T	5.1/8
$4.0<M<6.0$, all p_T	6.6/8
$5.0<M<8.75$, all p_T	0.5/6
$4.0<M<8.75$, $p_T<1.0$	10.4/8
$4.0<M<8.75$, $p_T>1.0$	7.5/8

The pion structure function is shown in Fig. 3. It has been fitted with the forms[7] $x_1\bar{u}^{\pi}(x_1) = ax_1^{1/2} \times (1-x_1)^b$ and $x_1\bar{u}^{\pi}(x_1) = a(1-x_1)^b$. The parameters for these and other fits discussed below are summarized in Tables I and II. Theoretical predictions for the exponent b are in the range 0–2.0.[8] It should be noted that the errors shown in Figs. 2, 3, and Tables I and II reflect only statistical uncertainties. An overall normalization uncertainty of 20% should also be applied to allow for A-dependence uncertainties and other systematic effects.

Using the values for a and b from fit 1 in Table I, we obtain, including normalization uncertainties,

$$\int_{0.25}^{1.0} x\bar{u}^{\pi^-}(x)\,dx = 0.14 \pm 0.03,$$

$$\int_{0.25}^{1.0} \bar{u}^{\pi^-}(x)\,dx = 0.31 \pm 0.07.$$

If the fit is used to extrapolate these results to $x_1 = 0$, the integrals are 0.20 ± 0.05 and 1.11 ± 0.27, respectively, for $0<x_1<1.0$. The first integral represents the fraction of the pion momentum carried by the $\bar{u}$ valence quark in the pion. Since both pion valence quarks have the same distribution function, the first integral indicates that about 40% of the pion momentum is carried by valence quarks.

The second integral provides a sum-rule check and a test of the color hypothesis. This integral over $0<x_1<1$ is expected to be 1 since a π^- contains one $\bar{u}$ valence quark. If quarks were colorless it would be 3 since $\bar{u}(x)$ was obtained through the use of Eq. (1). The value obtained is consistent with 1, but is sensitive to the unobserved low-x behavior of $\bar{u}^{\pi^-}(x)$.

As a consistency check, the pion and the nucleon structure functions obtained above can be used to calculate the μ-pair cross section as a function of mass and x_{F} using Eq. (2). Figure 4 shows the results of such a calculation compared to the data. The curves, calculated from the structure functions of Figs. 2 and 3, are in good agreement with the data. The inset to Fig. 4(a) shows the structure function applied to the whole mass range $M<9$ GeV/c^2. It falls below the data by a factor of 2 at 2 GeV/c^2 and a factor of 15 at 0.6 GeV/c^2.

We have investigated the sensitivity of our results to transverse-momentum and mass dependence by performing the structure function fit in different kinematic regions. The results are summarized in Table I. The variation of the pion structure function is described by the parameters from the fit to the form $ax_1^{1/2}(1-x_1)^b$. To gauge

TABLE I. Pion-structure-function fits.

	Fit	a	b
$4.0<M<8.75$, all p_T	$a\sqrt{x_1}(1-x_1)^b$	0.90±0.06	1.27±0.06
$4.0<M<6.0$, all p_T	$a\sqrt{x_1}(1-x_1)^b$	0.93±0.07	1.30±0.07
$5.0<M<8.75$, all p_T	$a\sqrt{x_1}(1-x_1)^b$	0.81±0.10	1.23±0.11
$4.0<M<8.75$, $p_T<1.0$	$a\sqrt{x_1}(1-x_1)^b$		1.17±0.08
$4.0<M<8.75$, $p_T>1.0$	$a\sqrt{x_1}(1-x_1)^b$		1.21±0.09
$4.0<M<8.75$, all p_T	$a(1-x_1)^b$	0.52±0.03	1.01±0.05

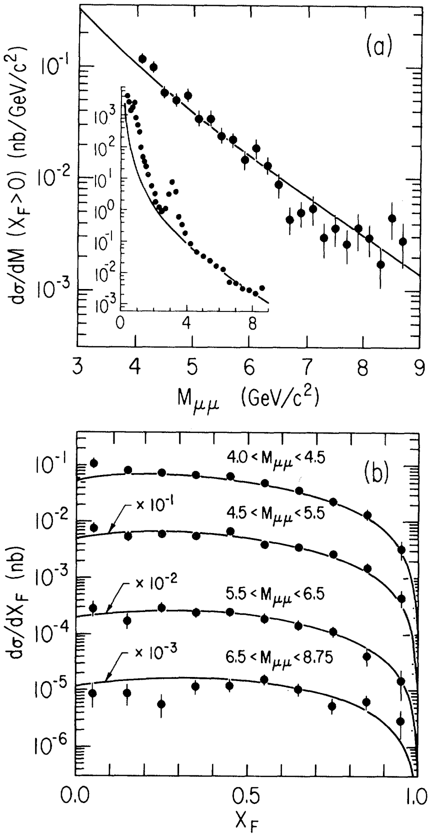

FIG. 4. Data from Ref. 1 are compared with expectations based on the structure functions determined from these same data (solid line). (a) Mass spectrum $d\sigma/dM$ vs M. The inset shows the extrapolation of the structure function to lower-energy measurements (Ref. 1 of Ref. 1), with the additional constraint that $x_F > 0.1$. (b) Feynman-x distribution $d\sigma/dx_F$ vs x_F.

the sensitivity of the nucleon function to mass and p_T effects, we give the χ^2 for the fit of the nucleon structure function to the calculated function shown in Fig. 2 (see Table II).

In mass, the intervals $4.0 < M < 6.0$ GeV/c^2 and $5.0 < M < 8.75$ GeV/c^2 were used. The mean mass in the lower interval is 4.7 GeV/c^2 while that in the upper interval is 6.0 GeV/c^2. No significant variation in either the pion or nucleon structure function was observed with mass. The fit was performed in two p_T regions: $p_T < 1.0$ and $p_T > 1.0$ GeV/c. The pion function is the same in both cases, within statistics. The nucleon function is slightly flatter in the higher-p_T region.

The effect of Fermi motion has been investigated with a Monte Carlo calculation.[9] It changes the power of the pion function by 0.02 and has a negligible effect on its normalization. It should be noted that the structure-function results depend on the applicability of Eq. (2), and as noted in the preceding Letter,[1] existing data are not in good agreement with the scaling prediction of the model.

In conclusion, we have used data on the pion production of μ pairs and the colored quark-antiquark annihilation model to determine the pion quark distribution function for the region $x > 0.25$. The shape of the nucleon structure function obtained is in good agreement with expectations. To 10% accuracy the pion quark distribution function shows no evidence for dependence on mass or p_T in the kinematic range of this experiment. The fraction of the pion momentum carried by its two valence quarks is comparable to the fraction of nucleon momentum carried by three valence quarks.

We are pleased to acknowledge the cooperation of the Fermilab Neutrino Department. Special thanks are due Jack Steinberger and the CERN-Heidelberg collaboration who loaned us the large multiwire proportional chamber detectors used in the upstream part of the spectrometer.

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[7] If the fit is to be extrapolated outside the region of

measurement, the square-root form is preferable since it leads to a finite value for the integral of the valence-quark function $u(x)$ over the range $0 \leq x \leq 1$. Several authors have suggested that the pion structure function should approach zero as $\sqrt{x}$. See, for example, P. V. Landshoff and J. C. Polkinghorne, Nucl. Phys. B19, 432 (1970); J. Kuti and V. F. Weisskopf, Phys. Rev. D 4, 3418 (1971).

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