Transverse Momentum and Angular Distributions of Hadrons in Muon-Proton Scattering and Tests of Quantum Chromodynamics

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The properties of the transverse momenta and angular distributions of hadrons produced in muon-proton scattering are compared with first-order quantum-chromodynamics calculations. The quantum-chromodynamics prediction for the Q^2 dependence of the average hadron transverse momentum squared agrees with the data provided a constant term is added in quadrature to the prediction. This additive term is attributed to the intrinsic transverse momentum of the quarks in the nucleon and to the transverse momentum inherent in quark fragmentation.

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The production of hadrons in muon-proton scattering can be described by a quark model. In its simplest form it is a separable two-step process. The muon scatters from one quark in the nucleon and the recoiling quark subsequently fragments into observable hadrons. The transverse momenta of the hadrons with respect to the virtual-photon direction are due to a combination of three factors. The first is the initial momentum of the quark and is a consequence of the observed fact that the quark is bound inside the proton. The second, similar in origin to the first, is the transverse momentum produced in the fragmentation of the recoiling quark. The initial transverse momentum of the quark may depend upon the Bjorken scaling variable $x = Q^2/2M\nu$, and the average transverse momentum of the hadrons depends on the fraction of the quark momentum carried by the hadron, $z = P_{\parallel}/P_{\max}$. The third factor is the radiation of a gluon by a quark, which can both change the quark direction and allow the hadrons to come from gluon fragmentation. This effect is expected to increase with the square of the four-momentum transfer, Q^2.

This Letter discussed two results from the Fermilab muon-scattering experiment[1,2] that throw light on these maters: The first is a measurement of the transverse momentum of hadrons as a function of Q^2; the second is a measurement of the angular distribution of the hadrons. These results are from the run with 219-GeV incident muons and extend those of Ref. 1. We presented them in a preliminary form at the Tokyo conference.[3]

The track finding and data analysis were similar to that described in Refs. 1 and 2. 10^4 events, with $s = W^2 > 100$ GeV^2, produced an average of one detected hadron above 7 GeV for each event. To avoid a background from halo muons, we cut the transverse momenta of the hadrons to $P_T^2 < 3$ (GeV/c)^2. We selected the value of the Feynman scaling parameter z by the cut $0.2 < z < 0.9$, independent of Q^2. The average, $\langle z\rangle$, is approximately constant as Q^2 changes. We quote statistical errors only. As Q^2 increases, the average value of the Bjorken scaling variable (x) increases from 0.005 to 0.5.

Figure 1 shows that the mean of the square of the transverse momenta, $\langle P_T^2\rangle$, increases with Q^2. Bremsstrahlung of photons is estimated, following the method of Ref. 1, to contribute less than 0.01 (GeV/c)^2 to $\langle P_T^2\rangle$. The increase could be a reflection of the change in x, but we suggest another explanation due to the third effect above. We have calculated $\langle P_T^2\rangle$ under various assumptions following the work of Mendez[4] who developed the Georgi and Politzer[5] procedure and we present curves A and B from his calculation. He used first-order-perturbation quantum chromodynamics (QCD), and a running quark-gluon coup-

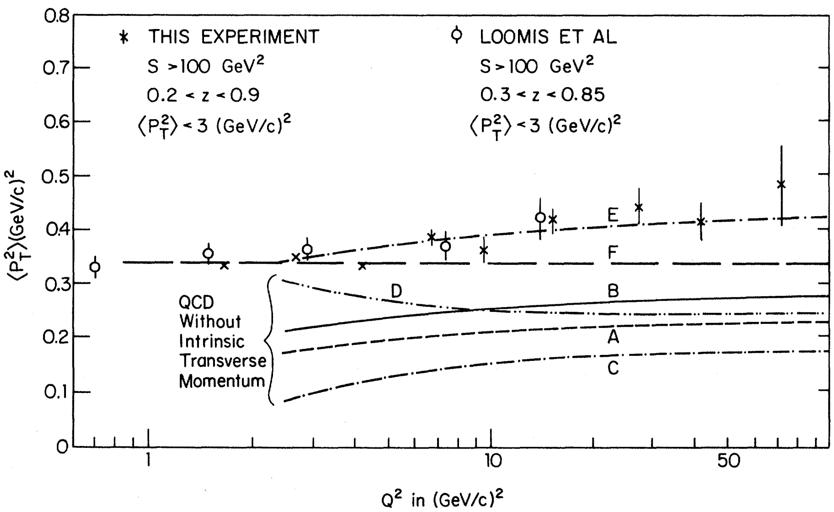

FIG. 1. $\langle P_T^2\rangle$ as a function of Q^2. Line A is the first-order QCD calculation of (4) with quark fragmentation only and no intrinsic quark momentum. Line B includes gluon fragmentation. Curves A and B use $\alpha_s = 12\pi/25\ln(Q^2/\Lambda^2)$ with $\Lambda = 500$ MeV. Curves C and D are the same as A but with $\Lambda = 200$ MeV and $\Lambda = 800$ MeV, respectively. Curve E is like curve B but with a constant $\langle P_T^2\rangle = 0.14$ (GeV/c)^2 added which is assumed to result from intrinsic quark momentum. Curve F is constant.

ling constant

$$\alpha_s = 12\pi/25\ln(Q^2/\Lambda^2),$$

with $\Lambda = 500$ MeV, and all the kinematic cuts used in our analysis [including $P_T^2 < 3$ (GeV/c)^2]. Curve A includes only quark fragmentation, and curve B is the extreme case where the gluon fragmentation is similar to quark fragmentation. Sehgal's[6] parametrization of the quark fragmentation function is used, and Hinchliffe and Llewellyn Smith's[7] parametrization of the parton distribution functions. Curves C and D are the same as A but with values of Λ taken as 200 and 800 MeV, respectively. Some insight into the behavior of the predictions with Λ is gained when it is realized that gluon bremsstrahlung does not occur in the completely forward direction and therefore contributes to $\langle P_T^2\rangle$. A constant (quark-gluon) coupling parameter α_s leads to a logarithmic rise of $\langle P_T^2\rangle$ as Q^2 increases. The running coupling constants (α) control the probability of gluon bremsstrahlung and if α decreases quickly with Q^2 the growth of $\langle P_T^2\rangle$ with Q^2 in the gluon bremsstrahlung process can be overcome.

In curve E of Fig. 1, we have added to Mendez's calculation (A) the arbitrary constant term 0.14 (GeV/c)^2. Curve F is a line of constant $\langle P_T^2\rangle$. Only curve E fits the data. We assume that the added constant term correctly describes the first and second contributions to $\langle P_T^2\rangle$ and that these contributions can be added in quadrature to the Mendez term.

We find that the variation with Q^2 is well described by Mendez's calculation. The constant part of $\langle P_T^2\rangle$ can be separated into the parts due to the initial quark momenta ($K_{T\,\mathrm{init}}$) and the quark fragmentation ($K_{T\,\mathrm{frag}}$): $\langle P_T^2\rangle_{\mathrm{const}} = \langle z^2\rangle\langle K_{T\,\mathrm{init}}^2\rangle + \langle K_{T\,\mathrm{frag}}^2\rangle = 0.14$ (GeV/c)^2, where $\langle z^2\rangle$ for our data is 0.16.

We can make the following observations about the two components of $\langle P_T^2\rangle_{\mathrm{const}}$.

(1) We set $\langle K_{T\,\mathrm{frag}}^2\rangle = 0$. Then $\langle K_{T\,\mathrm{init}}^2\rangle = 0.88$ (GeV/c)^2. This is clearly an upper limit.

(2) The naive quark model predicts that the transverse momentum in quark fragmentation is equal to the transverse momentum of hadrons about the jet axis in e^+e^- collisions where s and z in muoproduction are set equal to s and $2P_\parallel/\sqrt{s}$ in e^+e^- annihilation. In Fig. 25 of Ref. 1 we compared data on muoproduction with data of Hanson[8] and found that $\langle P_T\rangle$ muoproduction for $s > 100$ GeV^2 was essentially the same as $\langle P_T\rangle$ for e^+e^- annihilation at $s = 55$ GeV^2. We cannot, however, rule out a difference between the muoproduction and annihilation data at least to the level of 15% of the average square of the transverse momentum for hadrons in muoproduction. That is

$$\langle z^2\rangle\langle K_{T\,\mathrm{init}}^2\rangle < 0.05\ (\mathrm{GeV}/c)^2$$

or

$$\langle K_{T\,\mathrm{init}}^2\rangle \lesssim 0.3\ (\mathrm{GeV}/c)^2.$$

(3) Summaries of transverse momenta calculations[9] set $\langle K_T \rangle$ quark fragmentation at about $\langle K_{T\,\mathrm{frag}} \rangle = 0.3$ GeV/c by comparing fat and thin jets; since $\langle a^2 \rangle > (\langle a \rangle)^2$ this gives $\langle K_{T\,\mathrm{frag}}{}^2 \rangle \gtrsim 0.1$ (GeV/c)^2 and implies

$$\langle z^2 \rangle \langle K_{T\,\mathrm{init}}{}^2 \rangle \lesssim 0.04\ (\mathrm{GeV}/c)^2,$$

$$\langle K_{T\,\mathrm{init}}{}^2 \rangle \lesssim 0.25\ (\mathrm{GeV}/c)^2,$$

or

$$(\langle K_{T\,\mathrm{init}}{}^2 \rangle)^{1/2} \leq 0.5\ \mathrm{GeV}/c.$$

We find that our experiment is consistent with this general picture including QCD and that the average square of the transverse momentum of the quarks in the proton is of the order of 0.3 (GeV/c)^2. The uncertainty principle tells us that a quark confined in a proton with rms radius 0.8×10^{-13} cm must have an rms momentum greater than 0.13 GeV/c and an average squared momentum greater than 0.015 (GeV/c)^2. Our experiment suggests that the transverse momentum which quarks confined in the proton is about 3.5 times this minimum value. The average square of the transverse momentum of muon pairs produced in proton-nucleus interactions should be approximately twice the average square of the transverse momentum of the quarks bound inside the nucleons. Measurements[10] of $\langle P_T{}^2 \rangle$ for muon-pair production find $\langle P_T{}^2 \rangle \sim 0.8$–$1.4$ (GeV/c)^2 in reasonable agreement with our estimate.

The form of the angular distribution of hadrons about the virtual-photon direction is given by

$$d\sigma/d\varphi = A + B\cos\varphi + C\cos 2\varphi + D\sin\varphi,$$

where φ is the angle between the hadron and the lepton scattering plane, in the plane orthogonal to the direction of the virtual photon. D is a factor depending upon the muon polarization. We averaged positive and negative values of φ and therefore did not measure D. We report values of $\langle \cos\varphi \rangle = B/2A$ and $\langle \cos 2\varphi \rangle = C/2A$.

In the simplest models, neglecting transverse momenta of the quarks, B and C are zero. There are contributions to $\langle \cos\varphi \rangle$ and $\langle \cos 2\varphi \rangle$ from radiative processes (photon bremsstrahlung). Calculations (outlined in Ref. 1) yield estimates of $\langle \cos\varphi \rangle_{\mathrm{rad}} \simeq -0.02$ and $\langle \cos 2\varphi \rangle_{\mathrm{rad}} \simeq 0.02$ with errors about 0.01, assuming an isotropic distribution of hadrons around the virtual photon direction. We have not corrected for this effect. In QCD, there are contributions from quark recoils as a gluon is radiated.

In Figs. 2 and 3, we present $\langle \cos\varphi \rangle$ and $\langle \cos 2\varphi \rangle$ as derived from the data. Calculations from Mendez[4] are shown as solid lines. These calculations suggest that B and C should vary as $1/\ln Q^2$. C should be positive, and B could be positive or negative according to the relative multiplicities of gluon or quark fragmentation. We expect B to be negative for our experimental case. The agreements are poor.

Ravndal[11] wrote down the effect to be expected from initial quark momenta. He found that the values of $\langle \cos 2\varphi \rangle$ should be of the order of $\langle K_T{}^2 \rangle / Q^2$, depending on the relative magnitudes of the x and y components of K_T, and that $\langle \cos\varphi \rangle$ should be of the order of $(\langle K_T{}^2 \rangle / Q^2)^{1/2}$. This is the same order of magnitude as the effect from recoil as the gluon is radiated. Both effects must be included but since $\langle \cos\varphi \rangle$ and $\langle \cos 2\varphi \rangle$ represent interference terms, we cannot write down simple

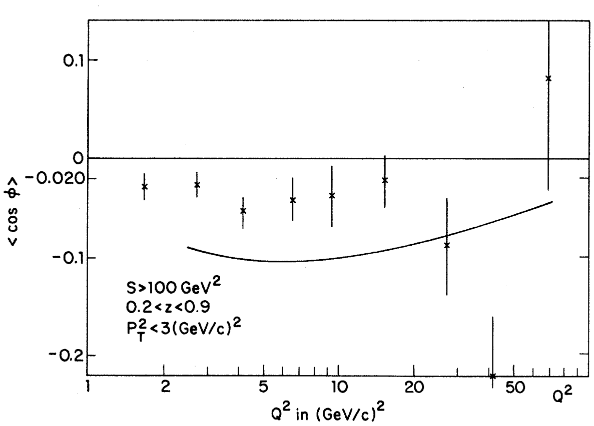

FIG. 2. $\langle \cos\varphi \rangle$ as a function of Q^2. The solid line is the first-order QCD calculation of Ref. 4.

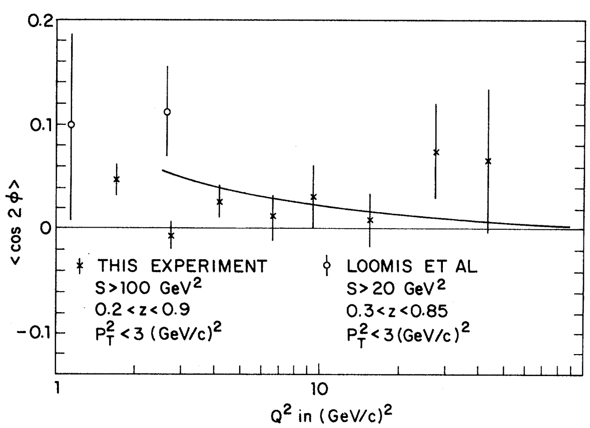

FIG. 3. $\langle \cos 2\varphi \rangle$ as a function of Q^2. The solid line is the first-order QCD calculation of Ref. 4.

additions of the two effects for comparison.

We conclude that the variation of P_T^2 with Q^2 from (1) is consistent with the recoil of quarks as they radiate gluons, but that this must be added to terms from the transverse momentum in the fragmentation process. The data are not consistent with a constant P_T^2 as the simple quark model suggests.

The angular distribution is a more sensitive test but its use must await a prescription for combining the two dominant effects according to a full QCD theory.

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[1]W. A. Loomis *et al.*, Phys. Rev. D 19, 2543 (1979).

[2]B. A. Gordon *et al.*, Phys. Rev. D 20, 2645 (1979).

[3]R. Wilson, in *Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, Japan, 1978*, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Physical Society of Japan, Tokyo, 1979), p. 306.

[4]T. Mendez, Nucl. Phys. B145, 199 (1978).

[5]H. Georgi and D. Politzer, Phys. Rev. Lett. 40, 3 (1978).

[6]L. M. Sehgal, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977*, edited by F. Gutbrod (DESY, Hamburg, Germany, 1977).

[7]I. Hinchliffe and C. H. Llewellyn Smith, Nucl. Phys. B128, 93 (1977).

[8]G. Hanson, in *Proceedings of the Thirteenth Recontre de Moriond, Les Arcs-Savoie, France, 1978*, edited by J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, 1978), pp. 15–42.

[9]H. Schopper, DESY Report No. DESY 79/79 (unpublished).

[10]K. J. Anderson *et al.*, Phys. Rev. Lett. 42, 944 (1979).

[11]F. Ravndal, Phys. Lett. 43B, 301 (1973).

Meson Structure Functions from High-Transverse-Momentum Hadron Interactions

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Data on large-transverse-momentum π^0 production by proton, pion, and kaon beams is used to extract the large-x behavior of meson structure functions. Good agreement is found with the proton and pion quark distribution functions obtained from deep inelastic and dimuon production experiments. This study provides the first look at the kaon structure function. A significantly faster falloff is found as x approaches unity than for that of pions.

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Recent experimental results on dilepton production by pion beams has made possible the extraction of the pion structure function.[1–4] If we assume the basic Drell-Yan process of quark-antiquark annihilation, the cross section is proportional to the product of pion antiquark and proton quark structure functions, each evaluated at a unique x value given by the dilepton kinematics. A further indication of the $q\bar{q}$ annihilation comes from the spin alignment exhibited by the dilepton decay angular distribution.[5] In addition, the large-x behavior of this alignment may even provide some information on the scale-breaking effects due to higher twist effects associated with quark binding in the pion.[6] The absolute normalization, however, is not so certain. It has been shown[7] that higher-order quantum chromodynamics (QCD) effects, namely collinear gluon radiation, can produce at least a factor of 2 uncertainty in normalization at present energies. Even so, the overall picture provides a rather satisfying description for large-mass di-

