# PHYSICAL REVIEW LETTERS

VOLUME 35 | 1 DECEMBER 1975 | NUMBER 22


## Inclusive Hadron Production in Inelastic Muon-Proton Scattering at 150 GeV/$c$*


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(Received 10 September 1975)



Inclusive hadron production in muon-proton inelastic scattering has been measured for $q^2 > 0.5$ (GeV/$c$)$^2$ and $10 < \nu < 135$ GeV. The results are presented in the form of the transverse momentum distribution of charged hadrons and the hadron invariant structure function $F(x')$. Results are given for different regions of $q^2$ and $s$.


We report here on part of a comprehensive muon-proton scattering experiment at the Fermi National Accelerator Laboratory. This paper discusses the results of measurements of the inclusive charged-hadron cross sections for the process $\mu^+ + p \to \mu^+ + h^\pm + x$.

Muon-proton scattering is dominated by the exchange of a single virtual photon and the kinematics can be characterized by $q^2$, the magnitude of the square of the four-momentum, and by $\nu$, the energy transferred by the photon. The differential muon scattering cross section $d^2\sigma_\mu/dq^2\,d\nu$ can be expressed in terms of a virtual-photon flux $\Gamma(q^2, \nu)$ and the virtual-photon total cross section: $d^2\sigma_\mu/dq^2\,d\nu = \Gamma(q^2, \nu)\sigma(q^2, \nu)$. In the center of mass of the virtual photon and proton, the kinematics of a produced hadron will be described by its momentum transverse to the photon direction $p_T$, by the total c.m. energy $s = M_p^2 + 2M_p\nu - q^2$, and by the value of a Feynman scaling variable $x' = p_\parallel^*/(p_{\max}^{*2} - p_T^2)^{1/2}$, where $p_\parallel^*$ is the hadron's longitudinal c.m. momentum and $p_{\max}^*$ is the maximum value this momentum can have. In calculating $x'$, we assume that every hadron is a charged pion since no identification of hadrons is made.

The number of hadrons per interacting virtual photon in a particular phase-space region is given by the invariant expression

$$\frac{1}{\sigma(q^2, s)} E \frac{d^3\sigma(q^2, s)}{dp^3} = \frac{1}{\sigma(q^2, s)} \frac{1}{\pi} \frac{E^*}{(p_{\max}^{*2} - p_T^2)^{1/2}} \frac{d^2\sigma(q^2, s)}{dp_T^2\,dx'}, \tag{1}$$

where $E$ and $p$ are the laboratory values of the hadron's energy and momentum, and $E^*$ is the hadron energy in the center-of-mass system.

The invariant structure function is defined by

$$F(x', q^2, s) = \frac{1}{\sigma(q^2, s)} \frac{1}{\pi} \int_0^\infty dp_T^2 \frac{E^*}{(p_{\max}^{*2} - p_T^2)^{1/2}} \frac{d^2\sigma(q^2, s)}{dp_T^2\,dx'}. \tag{2}$$

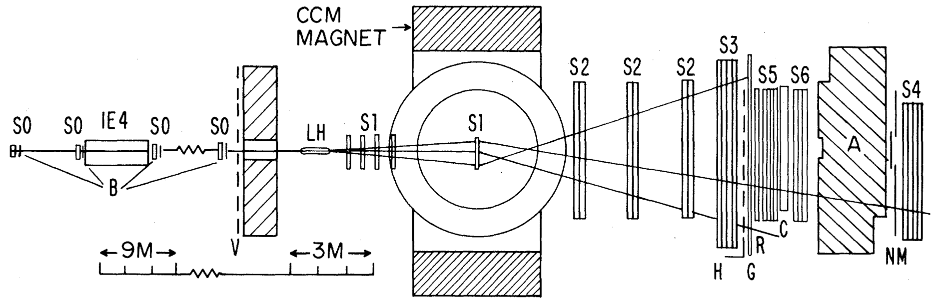


FIG. 1. Plan view of spectrometer. S0, S1 are multiwire proportional chambers; S2, S3, S4, S5, and S6 are multiwire spark chambers; B, G, H, M, N, and V are counter hodoscopes; 1E4, CCM are magnets; R, C, and A are absorbers.

The transverse-momentum distributions are given as values of

$$G(p_T^2, q^2, s) = \frac{1}{\sigma(q^2, s)} \frac{1}{\pi} \int_{x_1'}^{x_2'} dx' \frac{d^2\sigma(q^2, s)}{dp_T^2\, dx'}. \tag{3}$$

Figure 1 is a schematic drawing of the experiment (a complete description will be published elsewhere). Muons of 150 GeV/$c$ ($5\times10^5$ per accelerator pulse) strike a 1.19-m liquid-hydrogen target upstream of the spectrometer. The momentum of the incident muons is measured by the proportional chambers S0 and magnet 1E4. Muons that scatter through sufficient angle or lose sufficient energy strike counter hodoscopes G, H, and M. These counters and the beam counters B, in coincidence, trigger the apparatus. V and N counter hodoscopes veto halo muons and beam muons that do not interact. The multiwire chambers S1, S2, and S3 measure the momentum of hadrons and muons using magnetic bending in the magnet CCM (transverse-momentum kick of 2.2 GeV/$c$). The 2-m iron absorber A absorbs the hadrons and the scattered muon is identified using chamber S4. The spectrometer has high muon acceptance for $q^2$ and $\nu$ [except for $q^2 < 1.5$ (GeV/$c$)$^2$ where $\nu$ must be above 90 GeV]. Hadrons are accepted by our apparatus only in the region $x' > 0$. Events are selected for analysis as follows:

Triggers with suitably reconstructed incident- and scattered-muon tracks provide $\sigma(q^2, s)$ and candidates for hadron reconstruction. All hadrons are accepted with reconstructed tracks in spark chamber modules S2, S3 which link through the CCM to tracks in S1. In addition, appropriate hodoscope counters along the tracks must be struck and the tracks must pass through the muon-scattering vertex. The vertex resolution enables us to exclude from consideration all material except the liquid hydrogen, the target flask end windows, and the downstream end of the aluminum vacuum vessel. The liquid hydrogen constitutes 95.4% of the target mass as defined (verified by empty-target runs).

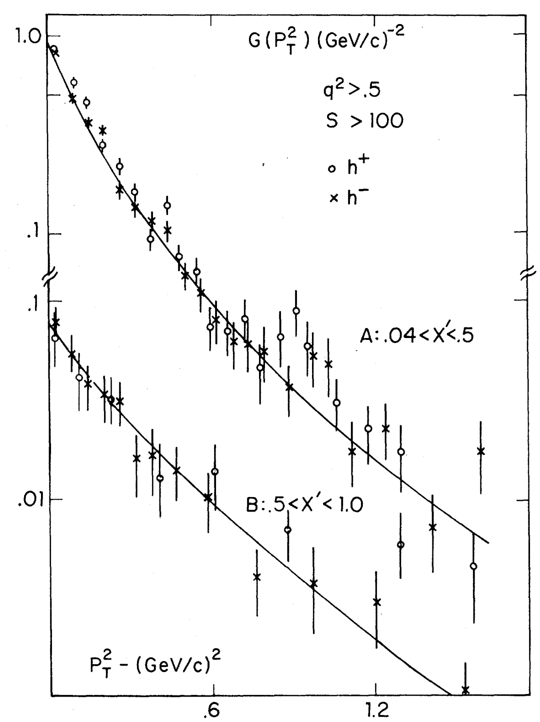


FIG. 2. Typical transverse-momentum spectrum for charged hadrons. Two $x'$ ranges are shown; the fits are of the form $A\exp[-b(P_T^2+M^2)^{1/2}]$ and apply to the negative hadrons as shown in Fig. 3.

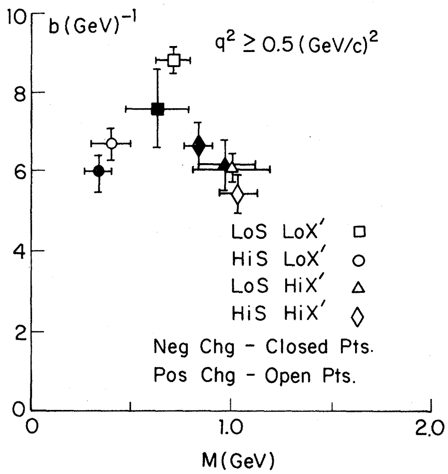


FIG. 3. Two-parameter fit to transverse-momentum distribution of inclusive hadrons [Eq. (4)]. Lo$x'$ means $0.04 < x' < 0.5$; Hi$x'$ means $0.5 < x' < 1.0$; Lo$s$ means $20 < s < 100$; Hi$s$ means $100 < s$.

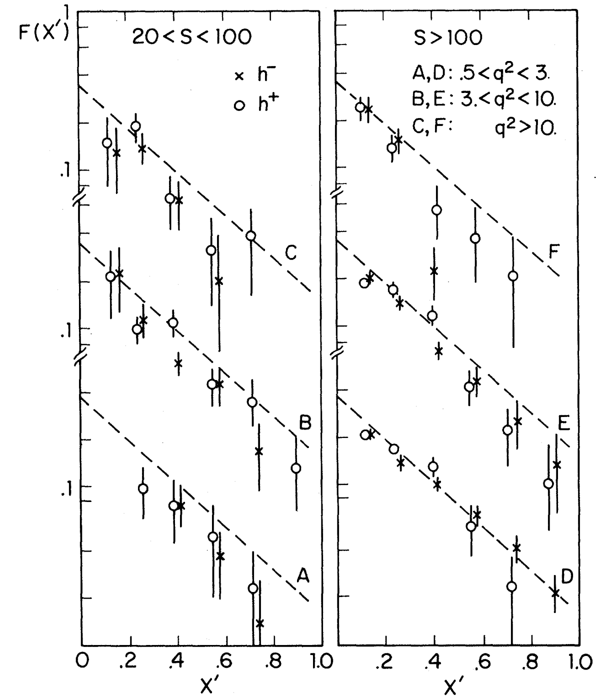


FIG. 4. Invariant longitudinal momentum spectrum for charged inclusive hadrons in several intervals of $q^2$ and $s$. The dotted line is $0.35\exp(-3.25x')$.

Only the electric charge and momentum of the hadrons is measured. Electron contamination from $\pi^0$ photon conversion is less than 3%. Muon-electron scattering events are eliminated by a kinematic cut demanding $q^2 \geq 0.5$ (GeV/$c$)$^2$. Corrections are made to the hadron spectra for acceptance, track reconstruction, and re-interaction in the target as follows:

The region in $x'$-$p_T^2$ phase space where the apparatus has nonzero acceptance is a strong function of the $q^2$ and $s$ of individual events. Observed hadrons are weighted inversely by their $x'$-$p_T^2$ acceptance determined from their event. Only muon scatters that have nonzero acceptance for a particular $x'$ and $p_T^2$ are used in the estimation of the corresponding $F(x')$ and $G(p_T^2)$.

6% of the muon-produced hadrons undergo secondary interactions in the target. The $x'$ of secondary hadrons is always reduced from that of the primary hadrons. The induced migration of data is such that any datum point is affected only by data points of smaller cross section. We correct only for the 6% loss. The overall reconstruction efficiency of the hadrons is estimated to be $(90 \pm 5)$%. The precision in the measurement of $x'$ and $p_T^2$ has negligible effect on the hadron distributions.

$F(x')$ is formed by taking the total number of hadrons near $x'$ having $q^2$ and $s$ within the region specified. This is divided by the total number of muons in the $q^2$-$s$ region along with appropriate kinematic factors. Weighting the muons and corresponding hadrons by the muon acceptance has no effect on the results. Radiative corrections are not made to the number of hadrons or to their apparent $x'$ and $p_T^2$. The number of muons is reduced by the calculated number of radiative elastic muon scatters, this calculation using the formulas of Mo and Tsai.[1] This correction is 30% or less.

The integrated useful muon flux for the present data is $2.1 \times 10^{10}$ muons. The results are presented in Figs. 2–5. Figure 2 shows $G(p_T^2)$. For $q^2$, $s$, and $x'$ regions studied, the best fits were found to be of the form

$$G(p_T^2, q^2, s) = G(p_T^2) = A\exp[-b(p_T^2 + M^2)^{1/2}]. \quad (4)$$

The results of these fits are shown in Fig. 3 as functions of $s$ and $x'$. No discernible $q^2$ variation was seen. In Fig. 3 the quantity $b$, typical of high-$p_T^2$ behavior, shows no variation with $s$ or $x'$. $M$, typical of low-$p_T^2$ behavior, seems to increase with $x'$. Equivalently the low-$p_T^2$ slope of the data decreases with $x'$.

$F(x')$ is shown in Fig. 4 broken into $q^2$-$s$ regions. The dashed line is $0.35\exp(-3.25x')$ allowing a comparison of the data in the different

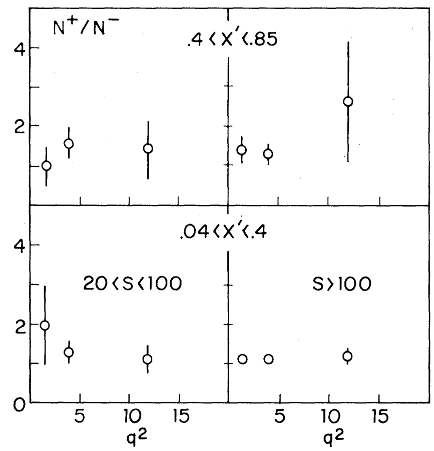


FIG. 5. Ratio of positive to negative charged hadrons as a function of $q^2$ for $s$ and $x'$. The $q^2$ intervals are the same as for Fig. 4.

regions. This line is also a good representation of $F(x')$ for negative hadrons as measured by Dakin *et al.*[2] at lower energies. This measurement shows no statistically significant variation of $F(x')$ with $q^2$ and $s$. Figure 5 shows the charge ratio $N^+/N^-$ as a function of $q^2$, $s$, and $x'$. For $x' < 0.4$ the ratio is 1, within statistics, as it must be for high-energy events. For $x' > 0.4$ the data suggest a small positive charge asymmetry whose dependence on $q^2$ and $s$ is unclear.

We conclude the following: (1) The hadron spectra show no substantial $q^2$-$s$ variation. (2) The spectra are in agreement with previous measurements[3] of virtual-photon–hadron production. For $x' > 0.4$ the charge ratios are consistent with the simple model of Dakin and Feldman.[4] (3) While there are differences, the data are typical of hadron-hadron interactions.[5]

We thank Fermilab for the use of their facilities and their energetic assistance. We are grateful for the technical assistance provided by the staffs at our home institutions and at the Rutherford Laboratory without whose expert help the experiment could not have been mounted.

*Work supported by the U. S. Energy Research and Development Administration, Contracts No. AT(11-1)-3064 and No. 1195, by the National Science Foundation, Contract No. MPS 71-03-186, and by the Science Research Council (United Kingdom).

†Submitted in partial fulfillment of Ph.D. requirements at the University of Chicago.

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# Search for Long-Lived Penetrating Neutral Particles*

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(Received 2 October 1975)

We report on a search for decays of long-lived penetrating neutral particles in the neutrino beam at Fermilab. We find an event rate consistent with background which corresponds to a fraction $(7\pm5)\times10^{-3}$ of $\nu_\mu$ ($\bar{\nu}_\mu$) scattering in liquid scintillator. This result poses an apparent contradiction to the observations of Krishnaswamy *et al.* in the Kolar Gold Mines.

We report on a search for long-lived, penetrating, neutral particles which emerge from the shielding of the neutrino beam at Fermilab and spontaneously decay within an emptied volume of our neutrino detector.[1] The experiment, which extends our previous search for long-lived particles,[2] has been motivated by the observation of Krishnaswamy *et al.*,[3] who have reported a special class of events induced by cosmic rays deep underground in the Kolar Gold Mines. Four