Measurement of Direct Muon Production in the Forward Direction*

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(Received 8 December 1975)

Direct muon production in the forward direction in 300-GeV proton-uranium collisions has been measured at Fermilab. The measurements were made for muons with $P_\perp$ less than 400 MeV/c and with momenta of 90 and 150 GeV/c. The values for the μ/π ratios are $\mu^-/\pi^- = (1.56 \pm 0.40) \times 10^{-4}$ and $\mu^+/\pi^+ = (4.7 \pm 1.1) \times 10^{-5}$ at 90 GeV/c; and $\mu^-/\pi^- = (3.8 \pm 2.1) \times 10^{-5}$ at 150 GeV/c. The ratio μ^+/μ^- at 90 GeV/c is 1.05 ± 0.1. The signal is too large to be accounted for by known processes.

The direct production of leptons in hadron collisions has been observed previously[1-5] at large $P_\perp$ (>1 GeV/c) and $x \simeq 0$.[6] These observations over the energy range $\sqrt{s} = 7.5-62$ GeV show the inclusive single-lepton yield to be at the level of about 10^{-4} of the pion yield and essentially independent of s and $P_\perp$, as well as A, the target atomic number.[2] Measurements of direct lepton production in the forward direction at 29 GeV[7] show a strong dependence on the outgoing muon momentum, with the direct production falling rapidly with increasing momentum.

Measurements of the forward muon production, as opposed to production at high $P_\perp$, are particularly interesting because contributions to the direct muon signal from dileptonic decays of massive vector mesons should be suppressed. Also, since the π yield increases at low $P_\perp$, a constant value of μ/π would imply a large total cross section for the production of direct muons. The experiment described here extends the measurements of μ/π to intermediate x ($\simeq 0.3$) and small $P_\perp$ (<0.4 GeV/c).

A schematic diagram of the beam and experiment is shown in Fig. 1. The first stage of the meson lab $M1$ beam line at Fermilab was used to transport a 300-GeV/c diffracted proton beam to a variable-density target of 23 2.54-cm-thick uranium plates. Immediately following the target, 3 m of steel was used to absorb hadrons produced in the target. An ion chamber upstream of the target monitored the incident proton flux

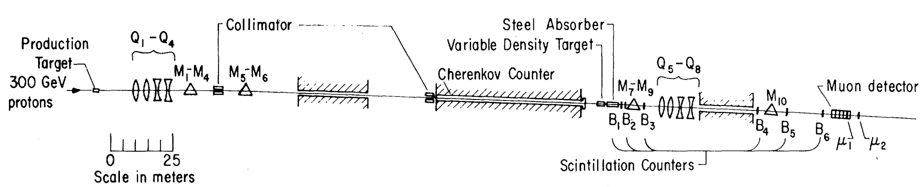

FIG. 1. The beam and experimental apparatus. The first stage of the beam line transported 300-GeV protons to the variable-density target. The beam line downstream of the target was used to select and identify muons.

which was typically 1×10^8 protons per pulse. The beam position and profile at the target were monitored by a segmented-wire ion chamber.

The downstream stage of the $M1$ beam line was used as a spectrometer to momentum analyze and transport produced muons to a muon detector located 90 m downstream of the target. Six small scintillators ($B1$–$B6$) with air light guides defined the trajectories of the muons in the spectrometer. The muon detector consisted of 5 m of steel and two large scintillators, μ_1 and μ_2. The spectrometer acceptance was 1.1 μsr at a mean production angle of 0° with a full width at half-maximum of 1.3 mr in the horizontal and 0.8 mr in the vertical. The momentum bite was $\pm7\%$. The $P_\perp$ acceptance falls to half height at about 300 MeV/c and is less than 2% at 800 MeV/c.

Directly upstream of the target, the beam passed through a 60-m-long helium-filled threshold Cherenkov counter set to count muons and pions, but not protons. An RCA 31000M photomultiplier was used to achieve single-photoelectron resolution. This counter eliminated muons in the incoming beam as a background.

Most of the data were taken with a trigger consisting of the coincidence $B\equiv B3\cdot B4\cdot B5\cdot B6$. For each event, the pulse heights of the Cherenkov counter and scintillators $B1$ and $B2$ were recorded on magnetic tape via a 2.5-km link to a PDP9 computer located in the proton lab. For these data $B1$ and $B2$ were included in B by an offline examination of the pulse height. Scalers and the ion chamber were recorded for each accelerator pulse.

The ratio of direct muons to pions was determined by varying the effective density of the U target. Data were taken in alternating runs with the target closed (density $\rho=0.88\rho_{\rm U}$, where $\rho_{\rm U}$ is the density of uranium) and target open ($\rho=0.25\rho_{\rm U}$). The slope of the muon yield versus $\rho_{\rm U}/\rho$ arises from muons created by the decay of pions and kaons. The average distance that these secondary particles travel before interacting is inversely proportional to the density of the target. Extrapolating to infinite density thus eliminates muons created in pion and kaon decays, with the intercept being the direct muon signal. If the shapes of the spectra of pions and kaons produced in the target are known, the slope of the curve of muon yield versus density can be used to determine the pion flux. Thus, the ratio of intercept to slope determines the muon-to-pion ratio.

The negative-particle flux was measured at reduced beam intensity by lowering the target and steel out of the beam and allowing the beam to strike a 15-cm-thick uranium target. The measured π^- flux from the 15-cm U target was fitted well[8] in the interval $x=0.3$ to 0.7 by the function $(1-x)^4$. The calculated ratio of direct muons to pions is not very sensitive to the spectrum; the ratio calculated using a somewhat steeper spectrum measured at 0.8 mrad from an aluminum target by Aubert *et al.*[9] differs from that calculated using the measured spectrum from uranium by less than 20%. The positive flux was not measured as it was not possible to discriminate positive pions from the more abundant secondary protons. Consequently, the π^+/π^- ratios of Aubert *et al.* and the π^- spectrum measured in this experiment were used to generate a π^+ spectrum.

The contribution from kaon decay was calculated by parametrizing the K^-/π^- and K^+/π^+ ratios measured by Aubert *et al.* as a function of x. We calculate the contribution from K^- to be 16% of that of π^- at $x=0.3$, from K^+ to be 25% of π^+ at $x=0.3$, and from K^- to be 2.3% of π^- at $x=0.5$. The μ/π ratio has been corrected for these contributions (see Table I).

The spectrum used in the slope calculation was determined with the thin target. In the case of the thick target, secondary interactions affect the calculated slope and may affect the intercept. The slope is increased by muons from pions and kaons in the later generations of the hadron shower. This contribution has been calculated by numerical integration of measured pion yields[10];

TABLE I. The corrected intercept-to-slope ratios and the calculated μ/π ratios at $x=0.3$ and 0.5 for negative muons and $x=0.3$ for positive muons.

Sign	p_μ (GeV/c)	Intercept (arbitrary units)	Slope due to $\pi+K$	Slope due to π only (slope$_\pi$)	Intercept / slope$_\pi$	$\mu/\pi\times10^4$
+	90	4.95 ± 0.51	1.66 ± 0.22	1.28 ± 0.22	3.88 ± 0.79	0.47 ± 0.10
−	90	4.72 ± 0.18	0.333 ± 0.077	0.303 ± 0.071	15.6 ± 3.7	1.56 ± 0.40
−	150	0.87 ± 0.12	0.085 ± 0.046	0.085 ± 0.046	10.2 ± 5.6	0.38 ± 0.21

the thick-target slope is 5% greater than the thin-target slope at $x=0.3$. The production of direct muons in the secondary showers changes the intercept. If the ratio of direct muons to pions is the same for pion-induced reactions as for proton-induced reactions, the slope-to-intercept ratio is unaffected by secondary interactions. The data have not been corrected for these contributions.

The data reduction consisted of determining the ratio $B\overline{C}$/(ion chamber) from the events recorded on magnetic tape, where $B\overline{C}$ represents the Cherenkov counter in anticoincidence with the trigger B. The Cherenkov-counter pulse-height threshold was set at two or more photoelectrons to eliminate a small but troublesome efficiency for protons. This requirement reduced the efficiency for muons from 95% to 81%; this efficiency was adequate as the fraction of raw events with a detected incoming muon was 0.12 for negatives and 0.26 for positives at $x=0.3$, and 0.06 for negatives at $x=0.5$. The data were corrected for accidental counts in the Cherenkov counter. These corrections were less than 5%. The data have been corrected for the small difference in detection efficiency (5%) between open- and closed-target positions.

Backgrounds associated with the beam halo were investigated by intentionally mis-steering the beam. Possible background associated with muons in the incoming beam was investigated by lowering the incident beam intensity and by varying the pressure in the Cherenkov counter confirming that incoming protons produced outgoing muons. This test also excluded off-axis beam muons as a background. There are two possible backgrounds which could not be investigated in the short time available: (i) the leakage from the back of the target of high-energy protons which then give rise to muons in the steel absorber just downstream; and (ii) protons which interact in material upstream of the target, giving rise to muons. Because the target was ~5 absorption lengths thick, (i) is expected to be very small. Background (ii) occurs only for material after the Cherenkov counter and in front of the target, as muons from interactions upstream of the Cherenkov counter are vetoed. The number of muons produced by material downstream of the Cherenkov counter was estimated by scaling the decay muons detected from the closed target (average absorption length 13.5 cm) by the fraction of protons which interact times the decay length. The muons from upstream sources were 12% of the total from π and K decay with the target open and 43% with the target closed. The data have been corrected for these contributions. A change of 20% in the relative absorption lengths leads to a systematic error of less than 10% at $x=0.3$, for positives, and of less than 5% for negatives at both $x=0.3$ and 0.5.

The corrected μ/(ion chamber) data are shown in Fig. 2. The final μ/π ratios are given in Table I. Note that the number of μ^+ is equal to the number of μ^- per incident proton at $x=0.3$, within statistics. This is expected, for example, if the direct muons are produced only in pairs.

There are two known sources of muons produced in the target itself: (i) Bethe-Heitler pair production of muons from γ rays coming mostly from π^0's, and (ii) the production of vector mesons ρ, ω, φ, and ψ which can subsequently decay to muon pairs. The contribution to the μ/π ratio from the Bethe-Heitler process can be calculated if the production cross sections for neutral and charged pions are known as a function of x. The calculation has been performed for a number of parametrizations of the pion cross sections, and at $x=0.3$, $\mu^-/\pi^-|_{\rm BH}=(1.0\pm0.4)\times10^{-5}$ and $\mu^+/\pi^+|_{\rm BH}=(0.6\pm0.3)\times10^{-5}$. At $x=0.5$, $\mu^-/\pi^-|_{\rm BH}$ drops to $\sim0.35\times10^{-5}$. Measurements[11] of electron and pion yields at $x=0.25$ in the forward direction are consistent with these calcula-

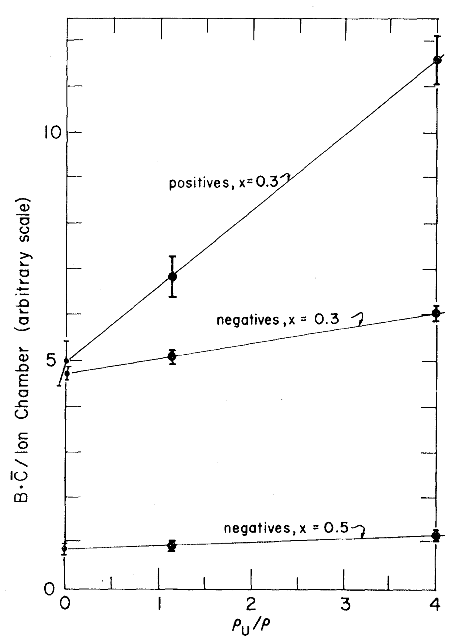

FIG. 2. The corrected (muon flux)/(ion chamber) versus inverse target density. The intercept corresponds to the direct-muon signal per incident proton (arbitrary units). Statistical errors only are shown—see text.

tions.

The production of the lighter vector mesons ρ, ω, and φ will also contribute to the "direct" muon signal. The cross section for inclusive ρ production in p-p collisions has been measured at 12 and 24 GeV by Blobel *et al.*,[12] and at 205 GeV/c by Singer *et al.*[13] On the basis of these measurements, the contribution from ρ^0 decay to the direct muon signal for the acceptance of the experiment reported here is calculated to be $<1.0\times10^{-5}$ for negative particles at both values of x. Contributions from ω and φ should be no larger. Because the ψ and ψ' are heavy, their contribution to the signal at small $P_\perp$ is negligible.

In conclusion, a nonzero direct muon signal in 300-GeV/c p-U collisions has been measured at values of $P_\perp \lesssim 400$ MeV/c. The ratio μ^+/μ^- is unity. The size of the signal is too large to be accounted for by the Bethe-Heitler process and vector-meson decay. The μ/π ratio at very small $P_\perp$ is comparable to that measured at larger values of $P_\perp$.

Note added.—Similar measurements from an experiment using a slightly different technique and with a different acceptance in $P_\perp$ and x as well as with a different target material have recently been published by Leipuner *et al.*[14] The results quoted here are larger than those quoted by Leipuner *et al.*, but because of the differences in the experiments are not necessarily in conflict with them.

*Work supported in part by the U. S. Energy Research and Development Administration and the National Science Foundation.

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