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Inclusive Production of $\pi^{\pm}, K^{\pm}, p, \bar{p}$ in High-Energy p-p Collisions

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We have measured the single-particle inclusive cross sections for $p+p\rightarrow\pi^{\pm}+X$, $K^{\pm}+X$, $p+X$, $\bar{p}+X$ in the low-$p_\perp$ region ($\lesssim 1.5$ GeV/c) as a function of the radial scaling variable X_R in p-p collisions at 100, 200, and 400 GeV at Fermilab. The measured π^+/π^- and K^+/K^- ratios are shown to be remarkably similar to the same ratios which have recently been measured at large $p_\perp$ at 90° in the center-of-mass system.

Measurements of inclusive hadron production in high-energy p-p collisions may be used to probe the constituent structure of the nucleon and to study the short-range interactions of these constituents. Many of the models for inclusive hadron production are limited to the large-$p_\perp$ region where the hard scattering of the constituents of the initial projectiles is supposed to reveal a simple underlying structure.[1] A complete understanding of these inclusive reactions must, however, cover the entire kinematic region, and hence must include the low-$p_\perp$ region as well as the large-$p_\perp$ region. It is, therefore, of interest to examine the inclusive production of hadrons in the low-$p_\perp$ region in light of what is known about these reactions at large $p_\perp$.

We have made measurements[2] of π production at both large and small transverse momenta from 15° to 110° in the center-of-mass frame. These data were most compactly described in terms of a radial scaling variable X_R ($X_R=E^*/E_{max}^*$, where E^* is the total energy of detected particle in the c.m. frame and E_{max}^* is the maximum energy available to the particle). This scaling variable led to a simple scaling behavior of single-particle inclusive cross sections in p-p collisions over a wide kinematic range.[3] Recently, results have been reported[4] at 200–400 GeV for particle production ratios in the reactions

$$p+p\rightarrow\pi^{\pm}+X,$$
$$p+p\rightarrow K^{\pm}+X,$$

at 90° in the c.m. frame. It is, therefore, of interest to measure these ratios at small (~0°) angles and investigate the similarities, if any, with the data at 90°. In this Letter we report the results of these measurements, make a comparison with the 90° data, and comment on the remarkable similarity of the two sets of data.

The data presented here have been taken with a 2.4-GeV/c double half-quadrupole spectrometer in the P-West area of Fermilab. An over view of the apparatus is shown in Fig. 1. By the forward-backward symmetry of p-p collisions in the c.m. frame, a modest low-momentum spectrometer can cover a large kinematic range by detecting "slow" particles produced in the backwards hemisphere. A well-collimated proton beam was allowed to interact with a 12.7-cm-long liquid-hydrogen target. The produced particles were detected and their species determined by a system

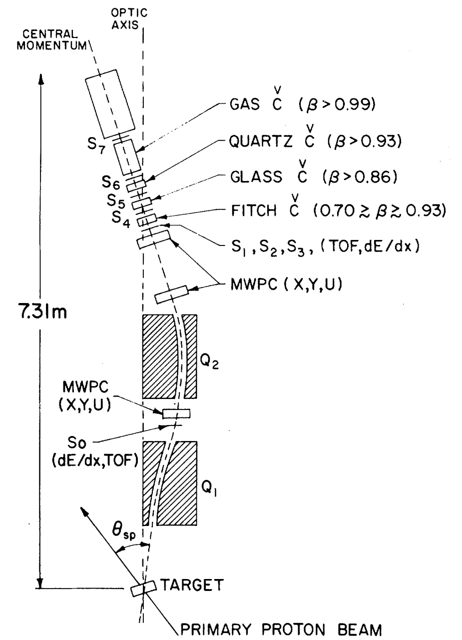

FIG. 1. The 2.4-GeV/c spectrometer. Shown are the two half-quadrupole magnets Q_1 and Q_2, and the locations of the scintillation and Čerenkov counters and the multiwire proportional chambers (MWPC).

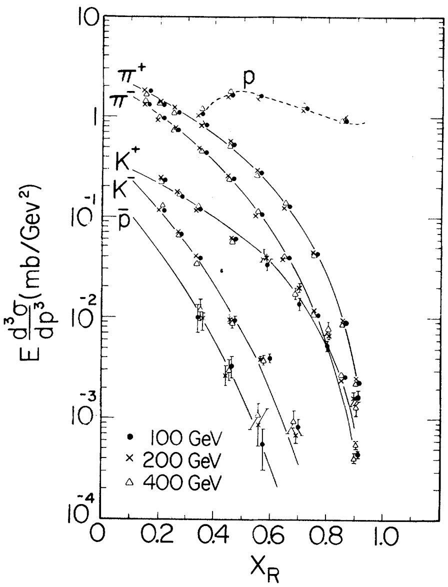

FIG. 2. The invariant cross sections $Ed\sigma/dp^3(p+p\to h+x)$ for $h=\pi^+$, $K^\pm$, p, $\bar{p}$ at constant $p_\perp=0.75$ GeV/c are plotted versus X_R. Data are shown for three incident proton energies: 100, 200, and 400 GeV. The lines through the data are the fits: $Ed\sigma/dp^3=B_h(1-X_R)^{n_h}$ given in Ref. 5. The dotted line through the proton data is to guide the eye.

of Čerenkov counters and scintillation counters inside the 2.4-GeV/c spectrometer. Nine proportional wire chambers allowed the detected hadron momentum to be determined to $\Delta p/p \lesssim 2\%$ over a momentum acceptance of $\pm 10\%$. The angle of the spectrometer could be remotely adjusted from 5° to 125° in the lab. The solid-angle acceptance was roughly 0.2 msr and was defined by the proportional wire chambers.

The absolute normalizations of the particle yields were determined by a Monte Carlo calculation of the spectrometer acceptance and by a measurement of the proton incident flux with two secondary-emission monitors which were calibrated by two beam toroids. The data have been corrected for nuclear absorption and decay in flight.[5]

Data were taken at fixed $p_\perp$ as a function of X_R in the region $0.05 \leq X_R \leq 1.0$. The $p_\perp$ values measured were 0.25 to 1.5 GeV/c in 0.25-GeV/c steps at 100-, 200-, and 400-GeV incident proton energy. Figure 2 shows the invariant cross sections $Ed\sigma/dp^3$ at a constant $p_\perp$ of 0.75 GeV/c vs X_R for $p+p\to\pi^+$, π^-, K^+, K^-, p, $\bar{p}$ +anything. (The limitation of space precludes plotting the data at the five other $p_\perp$ values). Only statistical errors are shown. The systematic normalization errors are estimated to be $\pm 10\%$ based on the reproducibility of the data. The values of the invariant cross sections are consistent with other data[3] which overlap for the same value of $p_\perp$ and X_R and s. It is evident from Fig. 2 that the invariant cross sections scale from 100 to 400 GeV for fixed $p_\perp$ and X_R. Furthermore, this scaling behavior is observed over the entire $p_\perp$ range of this experiment.[5]

These data provide the first opportunity to make a direct comparison of the particle ratios π^+/π^- and K^+/K^- vs X_R for both small-$p_\perp$ and large-$p_\perp$ data over the same range of center-of-mass energy. Generally it has been assumed that these two kinematic regions are characterized by long-range interactions described by Regge or diffractive scattering and short-range interactions described by the quark-parton model, and are, therefore, not related in an obvious way. Recently, however, there have been theoretical attempts[6] to provide a unified theoretical treatment of the two regions. In Fig. 3 we have plotted these invariant-cross-section ratios as a function X_R for both the data of this experiment for small $p_\perp$ ($0.25 \leq p_\perp \leq 1.5$ GeV/c are averaged together) in the fragmentation region and the data of Antreasyan *et al.*[4] at large $p_\perp$ ($0.77 \leq p_\perp \leq 7.67$ GeV/c) at 90° in the c.m. system. It is evident from Fig. 3

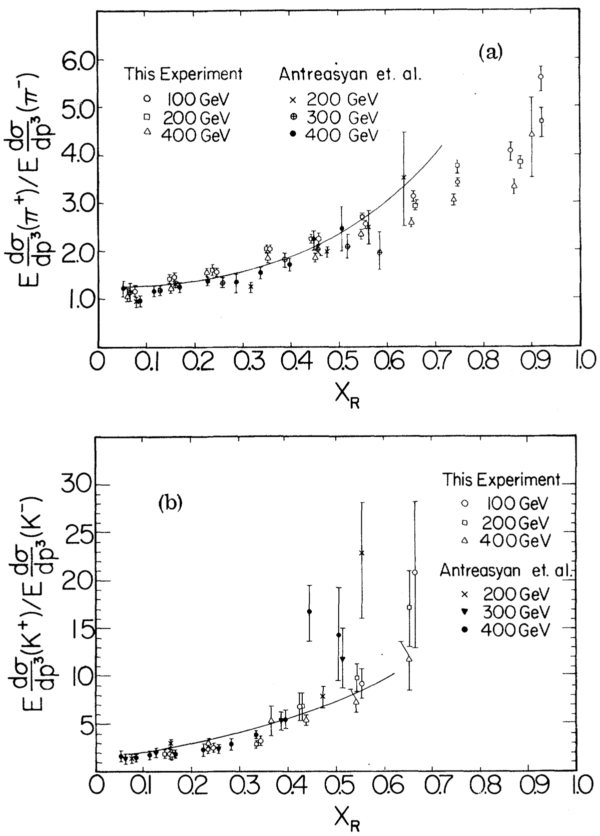

FIG. 3. The particle ratio: (a) π^+/π^- and (b) K^+/K^- from this experiment and that of Antreasyan *et al.* (Ref. 4) plotted vs X_R. The K^+/K^- ratio data at $X_R \geq 0.55$ from Ref. 4 have not been plotted since their error bars are very large. The curves are the predictions of Field and Feynman (Ref. 1) for the 90° region.

that the particle ratios in these two different kinematic regions are in remarkable agreement. This suggests that the ratios are uniquely dependent on the quantum-number requirements for particle production. The predictions of Field and Feynman[1] for the 90° region are shown in Fig. 3 to be in good agreement with both the 90° and 0° data. For $X_R \geq 0.6$ the present data tend to lie below the theoretical prediction for π^+/π^-. In fact, the π^+/π^- ratios appear to be approaching 5 for $X_R \to 1$. Field and Feynman[1] speculate on the possibility that the ratio $\pi^+/\pi^- \to 5$ as $X_R \to 1$. Farrar and Jackson[7] have discussed a quark-vector-gluon model in which the helicity of a fast quark ($X_R \sim 1$) is the same as that of the proton which implies the u/d quark ratio approaches 5 as $X_R \to 1$. This leads to the π^+/π^- ratio approaching 5, since it is determined by this quark ratio.

The theoretical predictions of Field and Feynman,[1] and Farrar and Jackson[7] are claimed to be valid for short-distance behavior. On the other hand, the data indicate that the particle ratios π^+/π^- are remarkably insensitive to angle and to transverse momentum. The particle ratios are, therefore, insensitive to the range of the interaction. It is therefore tempting to infer from the data that the alignment of the spin of the proton and the spin of the leading valence quark at large X_R is a general phenomenon of hadron interactions. This would imply that the K^+/K^- ratio would tend to ∞ as $X_R \to 1$ in agreement with the data of Fig. 3.

In conclusion, the single-particle inclusive cross sections for fixed $p_\perp$ ($\lesssim 1.5$ GeV/c) and X_R scale from 100- to 400-GeV incident proton energy. The particle ratios π^+/π^- and K^+/K^- vs X_R are independent of transverse momentum and angle. In particular the π^+/π^- ratio is approaching 5 and the K^+/K^- tends to infinity as X_R approaches 1.

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Direct Measurement of the π^- Form Factor

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We have measured the electromagnetic form factor of the charged pion by direct scattering of 100-GeV/c π^- from stationary electrons in a liquid-hydrogen target at Fermilab. The deviations from the pointlike pion-scattering cross section may be characterized by a root-mean-square charge radius for the pion of $\langle r_\pi^2\rangle^{1/2} = 0.56 \pm 0.04$ F.

We have performed an experiment in a 100-GeV/c negatively charged-pion beam at the Fermi National Accelerator Laboratory to measure the form factor of the pion by elastically scattering pions from the atomic electrons in a liquid-hydrogen target. The square of the pion form factor as a function of the square of the four-momentum transfer, q^2, is defined to be the π-e elastic (el) differential scattering cross section after radiation correction, divided by that predicted for a point (pt) pion;

$$(d\sigma/dq^2)_{\rm el} = (d\sigma/dq^2)_{\rm pt} |F_\pi(q^2)|^2 = \frac{4\pi\alpha^2}{q^4}\left(1-\frac{q^2}{{q_{\rm max}}^2}\right)\left|1-\frac{\langle r_\pi^2\rangle}{6}q^2+\cdots\right|^2.$$

In the second line the point-pion cross section is written in terms of the fine-structure constant α and $F_\pi(q^2)$ has been expanded in powers of q^2. In our experiment the maximum recoil energy of the electron was 84 GeV corresponding to ${q_{\rm max}}^2 = 0.086$ (GeV/c)^2. In this Letter we present data on the pion form factor in the range $0.03 \leq q^2 \leq 0.07$ (GeV/c)^2.

The charged pion is a particularly simple system compared to the proton. Its isovector character implies that it couples almost exclusively to the ρ meson. In the timelike domain the pion form factor has been well measured experimentally.[1] Measurements of the pion form factor at spacelike momentum transfers, coupled with analyticity, provide a useful test of the vector-dominance model. Furthermore, the size of the pion can be extracted directly from these spacelike measurements.

The first direct measurement[2] of the pion form factor by π-e elastic scattering obtained $\langle r_\pi^2\rangle = 0.61 \pm 0.15$ F^2. Our experiment provides an improved measurement through refinement of the techniques employed in the earlier experiment and by exploiting the higher-momentum-transfer values available at Fermilab.

The apparatus is shown in Fig. 1. The principal features of the experiment are as follows: