Relative Production of π^+, K^+, p, and $\bar{p}$ at Large Transverse Momentum in 200- and 300-GeV π^--p Collisions

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This Letter reports measurements of the ratios of π, K, and p production at large values of transverse momentum in π^--p collisions. The charge ratios, such as π^-/π^+, K^-/K^+, and $\bar{p}/p$ are seen to be quite different from those measured in p-p collisions. These ratios are sensitive tests of hard-scattering models, and are compared with theoretical predictions. The particle ratios have also been studied as a function of center-of-mass angle (θ^*) at $\theta^*=90°$, 77°, and 60°.

Inclusive measurements of single-particle hadron production at high transverse momentum (p_T) at the intersecting storage rings[1] and Fermilab[2] have played an important role in the development of theories of the underlying production mechanisms. One possible mechanism is the hard scattering of constituents of the hadron, as originally suggested by Berman, Bjorken, and Kogut.[3] The simplicity inherent in this idea, however, has not been readily apparent at presently available energies.[4]

In this paper, we present the first results of an experiment done at Fermilab to measure the production by incident pions of single-charged particles at high p_T. Pions, which contain valence antiquarks, were used as the projectile in the hope that the basic scattering process could be probed by comparing πp and pp interactions. In particular, the charge and type (e.g., π, K, p, or $\bar{p}$) of particles produced at large p_T are sensitive to the nature of the constituents which scatter.

The experiment described here has good particle identification and can measure the relative production of the various particle types. These ratios are presented in this paper. The data were taken with a 50-cm-long liquid-hydrogen target and span the p_T range $0.8 \leq p_T \leq 6.4$ GeV/c. Data which extend somewhat higher in p_T on Be, Cu, and W targets, as well as the H_2 cross sections, will be presented elsewhere.

The experiment was located in the experimental hall of the high-intensity pion beam in the proton west area at Fermilab. Typical beam intensities during the data taking were $(2-4)\times 10^9$ π^-/pulse at an energy of 200 GeV, with a maximum intensity of over 10^{10} π^-/pulse. The layout of the spectrometer is shown in Fig. 1. The spectrometer consisted of a quadrupole doublet, a bending magnet (16-mrad deflection), and a second bending magnet (also a 16-mrad deflection) with scintillation counters, drift chambers, and Cherenkov counters on either side.

The two Cherenkov counters C_A and C_B (see

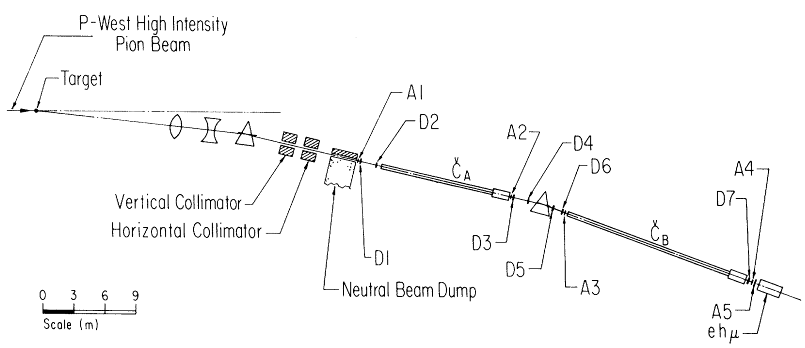

FIG. 1. The spectrometer layout. The A_i represent scintillation counters. The D_i are drift chambers. C_A and C_B are Cherenkov counters for particle identification. $eh\mu$ is a calorimeter for electron/hadron/muon separation.

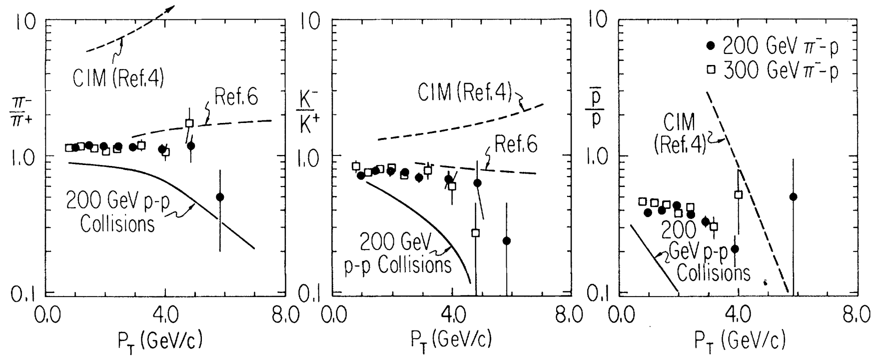

FIG. 2. The ratio of π^-/π^+, K^-/K^+, and $\bar{p}/p$ produced by 200- and 300-GeV π^--p collisions. Also shown are the corresponding ratios in p-p collisions, and the theoretical predictions of Field (Ref. 6) and Jones and Gunion (Ref. 4).

Fig. 1) were 14 and 20 m long, respectively. Each counter had two photomultiplier tubes, one sensitive to light emitted at angles of 0–9 mrad, and the other sensitive to angles of 9–30 mrad. With the Cherenkov counters we were able to separate simultaneously π's, K's, and p's ($\bar{p}$'s) at all attainable values of p_T. Electrons and muons were identified by means of a lead/Lucite calorimeter at the end of the spectrometer.

The solid angle of the spectrometer in the laboratory frame was 20 μsr, and the momentum bite was 22% (full width at half maximum). The drift chamber system gave a momentum resolution of better than 1.5% at laboratory momenta above 30 GeV/c. The momentum acceptance of the spectrometer was checked by analysis of special data runs which were taken with the central momentum of the spectrometer shifted by small amounts so that the cross section at the same value of p_T was measured in different regions of the momentum acceptance. The momentum scale of the spectrometer was calibrated by measuring the velocity of kaons of 25-GeV/c nominal momentum with the Cherenkov counters. We know the momentum scale to ± 1%.

The spectrometer viewed the target at an angle of 80 mrad which corresponds to 77° in the c.m. frame for 200-GeV incident pions, and to 90° for 300-GeV incident pions. Additional 200-GeV runs were taken with four dipoles in the beam line to change the targeting angle by ± 18 mrad, allowing data collection at c.m. angles of 90° and 60°, respectively.

The trigger consisted of the fourfold coincidence $A_1 \cdot A_2 \cdot A_3 \cdot A_5$ (see Fig. 1). In the subsequent analysis, tracks were identified in the seven drift chambers D_1–D_7 with an efficiency at low momentum of typically 93%. At high momentum, the trigger rate was dominated by accidental coincidences. These accidental triggers were cleanly eliminated in the analysis by requiring the tracks to be continuous in x and y, and to reconstruct back to the target.

The data have been corrected for decay in flight, for absorption in the spectrometer, and for contributions from the empty target. The decay-in-flight correction, for example, is 3.6% for pions and 30% for kaons at a laboratory momentum of 40 GeV ($p_T \simeq 3$ GeV). The spectrom-

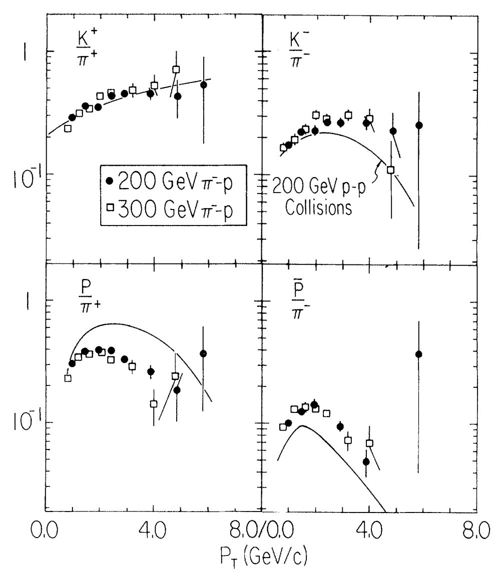

FIG. 3. The ratios of heavy particles (K and p) to pions produced in 200- and 300-GeV π^--p collisions. Also shown are the corresponding ratios in p-p collisions.

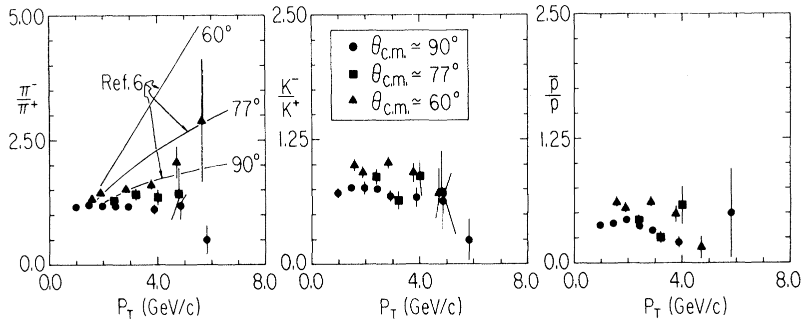

FIG. 4. The ratios π^-/π^+, K^-/K^+, and $\bar{p}/p$ as a function of p_T for c.m. angles of 60°, 77°, and 90°. The predictions of Field for π^-/π^+ are also shown.

eter absorption is approximately 10%. The empty-target correction grows slightly with p_T, and is 8% at $p_T = 1$ GeV/c, and 11% at $p_T = 4$ GeV/c. In the antiparticle/particle ratios presented here, however, these corrections cancel. Paired data runs were always taken for positive and negative particles to minimize other systematic errors.

Figure 2 shows the ratios π^-/π^+, K^-/K^+, and $\bar{p}/p$ where, for example, π^-/π^+ is the ratio of produced π^- to produced π^+, all with the same incident π^- beam. Also represented on the figure are the same ratios measured in p-p collisions.[5] All of the pion-induced ratios are more constant in p_T than in the proton-induced cases. This is natural if hard-scattering dominates, as the beam π^- can contribute a valence $\bar{u}$ quark to a π^-, K^-, or $\bar{p}$. Simple counting of the valence quarks gives $\pi^-/\pi^+ = 1.5$, and $K^-/K^+ = 0.5$; $\bar{p}$ production requires picking up two antiquarks, but the same simple counting of single valence quarks gives $\bar{p}/p = 0.33$. These numbers are in rough agreement with the data.

Figure 2 also shows predictions from a CIM calculation of Jones and Gunion[4] and a QCD calculation of Field.[6] The CIM calculations which had fit the production of each particle type in the p-p case very well (a special success being the prediction of a large proton flux) disagree with the pion-induced data by a large factor. The calculation of Field is in better agreement.

Figure 3 shows the particle ratios K^-/π^-, K^+/π^+, $\bar{p}/\pi^-$, and p/π^+, as well as the corresponding ratios in p-p collisions. As one would expect from the fast leading antiquark, K^- and $\bar{p}$ are produced much more copiously in π^--p than in p-p collisions.

In Fig. 4 we show the ratio of π^-/π^+ measured with 200 GeV π^- at laboratory angles of 98, 80, and 62 mrad, corresponding to c.m. angles of approximately 90°, 77°, and 60°, respectively. In contrast to the proton-proton case, the angular distribution in π^--p scattering need not be symmetric about 90°. If one makes the reasonable assumption that a particle observed at large x_T came from a valence quark, one can identify a π^+ as coming from the proton, a K^- or $\bar{p}$ as coming from the incident π^-, etc. Furthermore, if one assumes that the observed particle carries a large fraction of the scattered quark's momentum, then the particle's direction is close to that of the scattered quark. Hence the measured angular dependence would be strongly correlated with the angular dependence of the underlying hard-scattering process. Only a weak angular dependence is seen in contrast to the steeper predictions of Field. Figure 4 also shows the angular dependence of the ratios K^-/K^+ and $\bar{p}/p$.

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[6]R. D. Field, private communication. This model does not yet include baryon production and so has no prediction for the $\bar{p}/p$ ratio.

Evidence that High-p_T Jet Pairs Give Direct Information on Parton-Parton Scattering

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New results for parton transverse momentum obtained from two-jet high-p_T hadron events are presented. These results, and results for quark structure functions in the pion, are compared with results from dimuon production experiments. The results for the two types of experiments are very similar. This indicates that jet pairs give direct information on parton-parton scattering.

The search for high-p_T hadron jets and the study of their properties has been motivated by the hope that jet-pair events might provide the possibility of studying parton-parton scattering.[1] No other method of studying parton-parton scattering is known. In this Letter we report the first detailed results on parton transverse momentum, k_T, to be obtained in a hadron jet-pair experiment. These results and results on quark structure functions are compared with results from dimuon production. The close similarity of these results supports the conclusion that jet-pair events give direct information on parton-parton scattering.

Jets studied with calorimeters.—Recent calorimeter experiments have provided the first direct observation of jet events from hadron collisions.[2-4] Detailed study of these events shows that, with a calorimeter trigger of solid angle $\geqslant 1$ sr, well-defined, well-contained jets are found.[5,6] Because of the rapidly falling p_T spectrum, a calorimeter trigger preferentially selects narrow jets through the operation of a trigger bias effect pointed out by Dris.[7] The result is that for those jets which are detected there is little missing momentum and energy in undetected fragments, typically only a few tenths of a gigaelectronvolt.[8] Thus one can expect that in spite of residual uncertainties the momentum of a jet with such a calorimeter trigger may correspond closely to the momentum of a scattered parton. In the present report we examine further results and evidence bearing on the closeness of this correspondence.

Dijet transverse momentum p_T and parton transverse momentum k_T.—The apparatus consisted of a double-arm calorimeter array, which has been described elsewhere.[4] Data for this analysis were taken with a "double arm" jet trigger, which required the sum of the p_T magnitudes in all the calorimeter segments of the two arms to exceed an adjustable threshold. Both pp and πp collisions at beam momenta of 130 and 200 GeV/c were studied. For all of the results reported here, the calorimeter arms were centered near 90° c.m. The jet vector was determined by adding vectorially the momentum deposited in each calorimeter module. A fiducial-angle cut of ± 10° about the center of each arm in both $\theta_{\text{c.m.}}$ and φ was applied to the two jet vectors.

In essentially all the events, we have observed an approximate p_T balance in the two arms. This balance is a very prominent feature of the data, and in fact occurs with no software cuts of any

