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Comparison of High-p_T Events Produced by Pions and Protons

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We have measured high-p_T π^0's and jets with a two-arm calorimeter detector. Pions produce large-x_T jets more readily than do protons. We report the first direct measurement of two-arm jets. We find that the jet pairs have roughly balanced p_T and that pions produce jet pairs at more forward angles than do protons. These results give evidence for a constituent-scattering model, with constituents of higher average momentum in the pion.

We present results from an experiment performed at Fermilab comparing the production of high-p_T π^0's and jets by pion and proton beams. In a quark-scattering model one would expect more abundant production of particles of high x (both $x_T = 2p_T/\sqrt{s}$ and $x_L = 2p_{\parallel}/\sqrt{s}$) from pions than from protons.[1] Naively, this expectation is simply a reflection of the fact that pions have fewer constituents (only two valence quarks) than do protons (three valence quarks); and therefore

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on the average the constituents of the pion carry a larger fraction, x, of the incident momentum than do those of the proton.

In terms of constituent models for hadrons, the momentum distributions of the constituents are described by structure functions $G(x)$.[2] If the constituents of the pion have larger high-x components than do those of the proton, then $G_p(x)/G_\pi(x)$ will decrease at high x, and effects of two types can be expected: (1) The ratio of proton-produced events to pion-produced events will decrease as x_T increases. (2) If the pion's initial constituents tend to carry more momenta than the proton's, then the high-x_T products of the interaction will tend to go more "forward" for pion-produced events than for proton-produced events.

Strong effects of both types have been reported in a measurement of inclusive high-p_T π^0's.[3,4] The present experiment used a two-arm hadron calorimeter, each arm of substantial solid angle. Consequently, not only π^0's but jets as well were detected. This two-arm capability provided significant new results in the study of p/π production cross sections for high-p_T events.

The experiment was performed in the M-2 beam line at Fermilab. This present analysis considers data taken at +130 and +200 GeV/c. The apparatus, shown in Fig. 1, consisted of a two-arm segmented calorimeter array and six planes of drift chambers. Each calorimeter arm covered a solid angle of about 1.5 sr. A massive iron and concrete shield effectively eliminated beam halo particles and other upstream sources of background. Not shown in the figure are two independent differential Cherenkov counters used to identify pion and proton beam particles. The calorimeter was of modular construction, segmented (with independent readout) in area and depth. The left arm covered about 1.5 sr c.m. for π^0's and about 1.0 sr for other hadrons; the right arm covered about 1.5 sr for both. All modules were calibrated and balanced with beam particles to give uniform response to a few percent over the entire array.

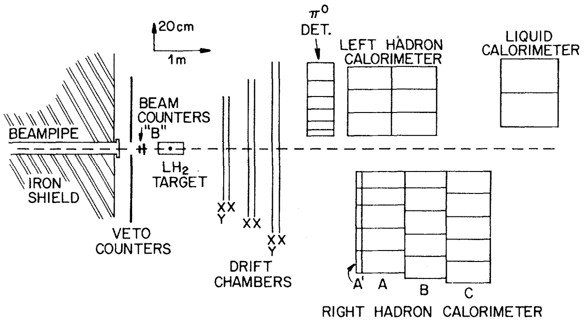

FIG. 1. Plan view of the apparatus. The anticounters vetoed charged particles emerging from the shield. The target was 45 cm of liquid H_2. Four of the six drift-chamber planes provided "x" information only; the other two planes provided coordinated "x-y" information from a delay-line readout. The right arm of the calorimeter consisted of 105 modules stacked in essentially a 5×5 array, four layers deep. The front layer consisted of Pb-scintillator modules; the remaining layers were Fe modules. The left arm consisted of 24 Pb modules (π^0 detector) followed over a large portion of its area by Fe modules.

Data were taken simulatneously with a number of triggers, each of which required the sum of the pulse heights in a particular group of modules, weighted by the sines of their angles in the lab ($p_T = p \sin\theta_L$), to be greater than some adjustable threshold. Signals were arranged to provide four trigger types: A right-arm trigger (R), a left-arm trigger (L), a summed trigger (L+R), and triggers from smaller groups of the modules forming single-particle triggers (SP) from both L and R sides. π^+- and p-induced events were recorded simultaneously, thus reducing the possibility of systematic errors in comparing their cross sections.

Before proceeding to a discussion of the results, we remark briefly on the general character of the events (more details are presented elsewhere[5-8]). (1) We find jet events similar to those reported by Bromberg *et al.*,[9] and consequently for the purpose of this Letter we adopt their definition of a jet event as an event in which a cluster of particles, rather than a single particle, carries high p_T into a solid angle of about 1 sr. (2) We also observer a similar cross-section ratio of jets to single π^0's, typically a few hundred to one. (3) Background contributions were studied in some detail. We found it possible to eliminate them readily for jet p_T values up to about 5 GeV/c. (4) We find both for the one-arm jets and for the two-arm jets that pion-induced and proton-induced jets of the same p_T are similar enough in size to produce no appreciable effect, in this experiment, on the p/π cross-section ratio.

As reported below, we observe strong differences in pion- and proton-initiated high-p_T jet events. From point (4) above, we conclude that these differences are to be associated with differences in the pion and proton structure functions of the high-p_T groups.

We first show results for a sample of π^0-like events.[10] The results for the p/π production cross-section ratio,

$$R_{\pi^0} \equiv \sigma(pp \to \pi^0 + X)/\sigma(\pi^+ p \to \pi^0 + X),$$

are shown in Fig. 2 for events taken in the 75° to 90° c.m. region at +130 and +200 GeV/c. The results agree with the 90° results of Donaldson *et al.*[3,4] to within the systematic error in our x_T scale, which is due to energy calibration uncertainties, amounting to a maximum of 10% for individual modules.

In Fig. 3(a) we plot our results for the ratio

$$R_{\text{jet}} \equiv \sigma(pp \to \text{jet} + X)/\sigma(\pi p \to \text{jet} + X)$$

as a function of x_T, again near 90° c.m. The ratio R_{jet} has basically the same shape as R_{π^0} but the curve is shifted to higher x_T. In Fig. 3(a) we show again the solid curve[1] of Fig. 2, along with a dashed curve which is the solid curve shifted to the right by a factor of 1.4 in x_T. The fact that the two distributions R_{π^0} and R_{jet} have approximately the same shape may indicate that the high-p_T single π^0's originate from jets in which a roughly constant percentage of the jet p_T has been given to the single π^0. Other explanations are also possible. We note, for example, that some of the additional p_T observed for jet events compared to π^0 events for a given value of R may arise from particles associated with beam and target jet fragments. Our analysis is not sufficiently refined to estimate the magnitude of this beam jet contribution, nor its variation with x_T.

For comparison we have plotted the results for R_{jet} of Bromberg *et al.*[9] in Fig. 3(b). Their results are not in close quantitative agreement with our data, although they do show the same general trend with increasing x_T. A plausible reason for this discrepancy lies in the difference in acceptance of the two experiments; the acceptance of the calorimeter of Bromberg *et al.* is substantially smaller than ours.[12] Consequently, in their detector a measured jet of, say, $x_T = 0.4$ may originate from a jet of "true" $x_T = 0.5$; this would result in an incorrectly small value of R_{jet} at $x_T = 0.4$.

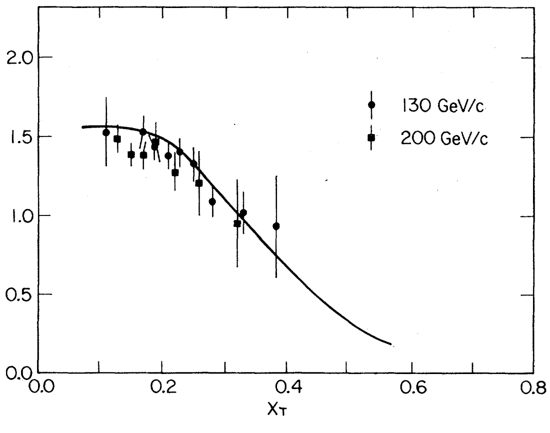

FIG. 2. Results of this experiment for $R(\pi^0)$ as defined in the text, near 90° c.m. The curve is a calculation of Field and Feynman (Ref. 11), which agrees closely also with data of Donaldson *et al.* (Ref. 3).

Finally we discuss some two-arm correlation data taken with the L+R trigger at +130 GeV/c with the total p_T (sum of the p_T magnitudes in the two arms) selected to be in the interval ≈5.0 to 5.5 GeV/c. For such a selection we find that the momenta in the two arms balance, with each arm having an average p_T of 2.6 GeV/c, and a full width at half-maximum of 1.2 GeV/c.[5] It is important to note that this equality of the p_T in each arm is not forced by any aspect of the detector, trigger, or analysis.

We first bin the events according to the observed directions of the jet vector polar angles in the overall c.m. system on the left (θ_L^*) and right (θ_R^*). (These angles are calculated neglecting rest-mass effects for individual particles.) The p/π ratio $R_{\text{jet}}(\theta_L^*, \theta_R^*)$ is plotted in Fig. 4 as a function of θ_R^* for bins of constant θ_L^*. These

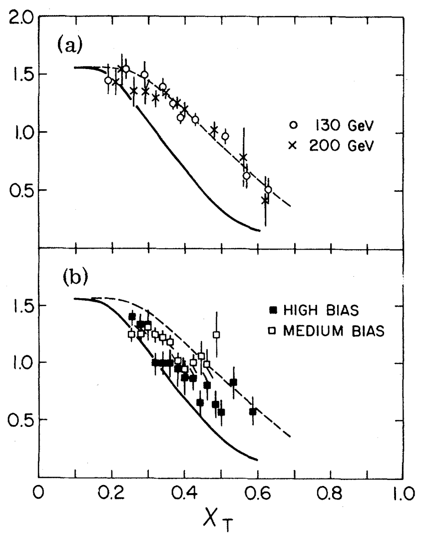

FIG. 3. Results of (a) this experiment, (b) Bromberg *et al.* (200 GeV; see Ref. 9), for $R_{\text{jet}}(x_T)$. The solid curve is the calculation of Field and Feynman and the dashed curve is the same calculation shifted to the right by a factor of 1.4 in x_T.

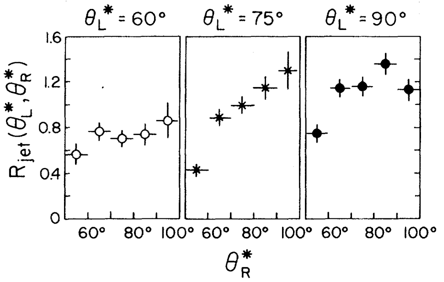

FIG. 4. Angular correlation results of this experiment for two-arm jets, at 130 GeV. The variables are defined in the text.

angular correlation data show, for a given jet direction on the left, whether the opposite-side jet emerges preferentially at different angles for incident protons than for incident pions. It is seen that at small $\theta_L{}^*$ and $\theta_R{}^*$ there is a larger cross section for pion-induced events ($R_{\text{jet}}<1$), and that at larger $\theta_L{}^*$ and $\theta_R{}^*$ there is instead a larger cross section for proton-induced events ($R_{\text{jet}}>1$). That is, in these two-arm events at this x_T pions produce high-p_T events at more forward angles than do protons.

In summary (1) we have measured the ratio R_{π^0} for pion- and proton-induced events and found it to be consistent with a previous experiment.[3] (2) We have also measured R_{jet} and found that it has a form similar to that of R_{π^0} but at perhaps 40% higher p_T. The value of R at high x_T indicates that pions produce high-p_T jet events much more readily than protons. (3) We observe in our two-arm data an approximate balance of the p_T magnitudes in the two arms. (4) From our measurement of $R_{\text{jet}}(\theta_L{}^*, \theta_R{}^*)$ we observe that pions produce correlated two-arm high-p_T events at more forward angles than do protons. From points (3) and (4) we conclude that the two-arm jet data give strong evidence for hard scattering of hadron constituents rather than simply for a phase-space type of momentum conservation effect. All of these results taken together indicate that the high-p_T events we are observing have characteristics in agreement with constituent-scattering models, and that the constituents of the pion which produce these events have on the average a significantly higher fractional momentum x than those of the proton.

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