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High-p_T Pion Production in $\pi\pi$ Interactions

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Abstract

Charged pion production in high energy $\pi^-\pi^-$ interactions is studied in the p_T region of 1 - 2 GeV/c. The characteristics of pion production in $\pi^-\pi^-$ interactions are compared with those in π^-p and pp interactions. The p_T-dependence of pion production in these reactions follows a systematic trend which indicates that high-p_T pion production for $\pi\pi$ interactions as well as for πp and pp interactions proceeds via quark-quark scattering as predicted by QCD.

Particle production at high transverse momentum (p_T) is believed to result from the interaction of hadronic constituents [1]. Single-particle inclusive data from the CERN Intersecting Storage Rings [2] and from Fermilab [3, 4] have been analyzed in terms of this hypothesis. In these experiments, particle production in proton-proton, proton-nucleus, and pion-proton interactions has been studied. To investigate the role of hadronic constituents in high-p_T particle production it is important to compare reactions produced by initial state target and beam particles having different internal structure. We report here the results of a study of large p_T (1 - 2 GeV/c) inclusive $\pi^\pm$ production, at c.m. angles centered around 90°, in high energy $\pi^-\pi^-$ interactions and compare these results with π^0 production in pp and πp reactions at comparable energies[4].

Our data are derived from π^-p interactions at beam momenta of 100, 200, and 360 GeV/c. These experiments were performed at Fermilab utilizing the 30-in. hydrogen bubble chamber wide-gap spark chamber hybrid system. Details of the data analysis have been previously reported [5, 6]. For the present analysis, we use samples of about 29,000 events of all charge topologies at 360 GeV/c, 17,000 events at 200 GeV/c, and 7,700 events at 100 GeV/c.

In Fig. 1, we compare our inclusive $\pi^\pm$ production data for π^-p interactions with corresponding π^0 production data. The invariant cross sections for the charged pion production near 90° ($-0.34 \leq \cos\theta_{cm} \leq 0.34$) for our 100 and 200 GeV/c data are plotted in Fig. 1, where the averages of π^- and π^+ cross sections are shown. We also show the π^0 production cross sections

of Donaldson et al. [4] obtained near 90° in 100 and 200 GeV/c $\pi^- p$ interactions. It is evident that our p_T distributions for average π^- and π^+ production at 100 and 200 GeV/c are quite consistent with the p_T distributions for π^0 production at the same energies. Our new data for high-p_T pion production in 360 GeV/c $\pi^- p$ interactions are also shown.

In order to study high-p_T $\pi^\pm$ production in $\pi^-\pi^-$ interactions, we select events corresponding to the reaction $\pi^- p \to \Delta^{++}(1236) + X^{--}$. In a previous paper [6], it was shown that the production of the recoil system X^{--} is well described by the one-pion-exchange mechanism. For the virtual $\pi\pi$ interaction the mass M_X recoiling against the Δ^{++} represents the total energy in the $\pi\pi$ c.m. frame. We assume that all events having $1.12 \leq M(\pi^+ p) \leq 1.32$ GeV with $|t| < 1$ GeV^2 correspond to the reaction $\pi^- p \to \Delta^{++} + X^{--}$ where X^{--} is produced via one pion exchange. From our entire sample (100, 200, and 360 GeV/c data), we have 2,700 events corresponding to this reaction. The M_X distributions for these events are shown in Fig. 2. The number of charged pions associated with the X^{--} systems in these events is ~14,000; these are utilized for the study of the inclusive reaction

$$\pi^-\pi^- \to \pi^\pm + \text{anything}. \qquad (1)$$

Fig. 2 shows that most of these events are at the high M_X or high $\sqrt{s}$ (for the $\pi\pi$ system). We select events with $5.0 \leq M_X \leq 17.0$ GeV ($\langle \sqrt{s} \rangle = \langle M_X \rangle = 10.3$ GeV) for the study of $\pi^\pm$ production in high energy $\pi^-\pi^-$ interactions. We note that the inclusive pion production in 100 GeV/c πp and pp interactions at Fermilab ($\sqrt{s} = 13.7$ GeV) is in the similar energy region.

The inclusive $\pi^\pm$ production in reaction (1) can be described in terms of $\cos\theta_{c.m.}$ and p_T calculated with respect to the beam direction in the rest frame of X^{--}. The pions produced at $-0.6 \leq \cos\theta_{cm} \leq 0.6$ are selected to obtain the $\pi^\pm$ cross section near $\theta_{cm} = 90°$ and to study this invariant cross section as a function of p_T for $p_T > 1$ GeV/c. In Fig. 3a we show the p_T distribution (arbitrary units*) for $\pi^\pm$ production in $\pi^-\pi^-$ interactions for our sample with $\langle \sqrt{s} \rangle = 10.3$ GeV. The π^0 production data of Donaldson et al. for 100 GeV/c $\pi^- p$ and pp interactions at $\sqrt{s} = 13.7$ GeV are shown on the same plot and the p_T-dependences of the three processes may be compared.

To compare the pion production data in the different reactions, we parametrize the invariant cross section $f(p_T) \equiv E d\sigma/d^3p$ as

$$f(p_T) = c\, p_T^{-n}. \qquad (2)$$

From a least squares fit to the data we obtain $n = 6.2 \pm 1.0$ for the $\pi^-\pi^-$ case, $n = 7.46 \pm 0.15$ for the $\pi^- p$ case, and $n = 7.93 \pm 0.13$ for the pp interactions. The "best fits" to the data are shown as solid curves in Fig. 3a. The lower value of n for the $\pi^- p$ interaction as compared to that for the pp interaction has by now been well established experimentally; this is readily understood from a theoretical point of view in terms of the hadronic structure of pions and protons. The constituents of the pion carry, on the average, greater momentum than those of the proton. In $\pi^-\pi^-$ scattering, the constituents involved have even higher average momentum than in $\pi^- p$ scattering. Thus the still lower value of n for $\pi^-\pi^-$ scattering reinforces the conclusion that

* We have not attempted to extract the $\pi^-\pi^-$ cross section by Chew-Low extrapolation, considering the limited statistics of our sample.

the p_T-distribution at the same energy of the incident particles becomes shallower as the constituents involved in the process become harder.

We may also compare pion production data in $\pi^-\pi^-$ interactions with the predictions of the quark-quark scattering model of Field and Feynman [7] which has already proven to be successful in πp and pp interactions. We have calculated the invariant pion production cross sections in $\pi^-\pi^-$, π^-p and pp interactions from the quark-quark scattering model using a procedure given by Owens et al. [8], which involves a Q^2-dependent strong coupling constant $\alpha_s(Q^2)$, Q^2-independent quark fragmentation functions, and appropriate quark structure functions. For the proton we use Q^2-dependent quark structure functions suggested by Buras and Gaemers [9], and for the pion we use quark structure functions obtained by Newman et al. [10] from muon pair production data in π^-p interactions. The results of the calculations are shown in Fig. 3a in the inset (dashed curves). These curves yield value of $n = 8.1$ for the $\pi^-\pi^-$ case, $n = 8.6$ for the π^-p case, and $n = 9.1$ for the pp interactions. These values increase progressively in the same order as the fits to the data. Moreover, the data show the change in n is $\Delta n = 1.2 \pm 1.0$ between the π^-p and $\pi^-\pi^-$ interactions and $\Delta n = 0.47 \pm 0.2$ between the pp and π^-p interactions; the model yields $\Delta n = 0.5$ for both cases. We thus conclude* that the model predicts the trend of the p_T dependence for different reactions quite well.

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* A quantitative agreement between the data and the model calculations can only be expected at much higher p_T ($p_T > 3$ GeV/c) (see Ref. 8). At present the calculations, which involve only first order QCD corrections, adequately account for the high p_T data because of the smallness of the coupling constant at high Q^2. For a quantitative prediction in the p_T region of 1 - 3 GeV/c, one would need to include higher order QCD terms.

In Fig. 3b we plot the ratio of π^+ to π^- cross sections as a function of p_T for $\pi^-\pi^-$ scattering. The curve shows results from the model calculation described in the previous section. We find that the model describes the data at high p_T rather well. We note that this ratio is insensitive to the details of the input functions used in the model calculation and hence the prediction by the theory is rather unambiguous.

In summary we have studied, for the first time, pion production in high energy $\pi^-\pi^-$ interactions in the p_T region of 1 - 2 GeV/c. We have compared the characterisitcs of $\pi^-\pi^-$ scattering with those of π^-p and pp interactions. We find that the p_T-dependence of pion production in the different reactions follows a systematic trend. This trend is consistent with the notion that high-p_T pion production for $\pi\pi$ interactions as well as for πp and pp interactions proceed via quark-quark scattering as predicated by QCD.

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Figure Captions

Fig. 1 Invariant cross section for π^0 and π^* production as a function of p_T in $\pi^- p$ interactions (a) at 100 GeV/c, (b) at 200 GeV/c, and (c) at 360 GeV/c.

Fig. 2 Distribution of M_X, the effective mass of X^{--} in the reaction $\pi^- p \to \Delta^{++} + X^{--}$ for 100, 200, and 360 GeV/c data. These events correspond to $|t_{p\Delta}| < 1.0\ \mathrm{GeV}^2$, where $t_{p\Delta}$ is the square of the four-momentum transfer between the baryons.

Fig. 3(a) Invariant pion production cross section as a function of p_T for $\pi^-\pi^-$, $\pi^- p$ and pp interactions at about the same center of mass energy. The solid curves are fits to the data. The results of model calculations (see text) are shown in the inset (dashed curves).

(b) Ratio of π^+ to π^- production cross section as a function of p_T in $\pi^-\pi^-$ interaction at $\sqrt{s} \approx 10.3$ GeV. The dashed curve corresponds to model calculation (see text).

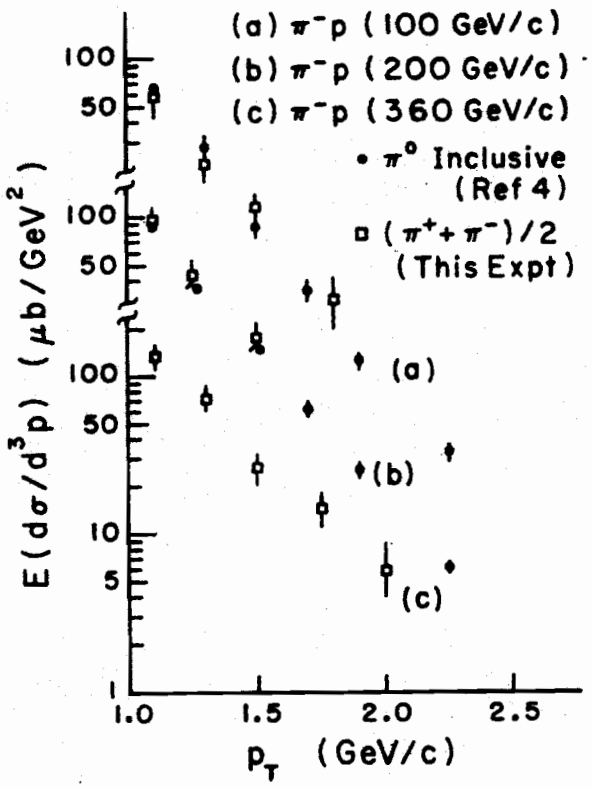
(a) π⁻p (100 GeV/c)
(b) π⁻p (200 GeV/c)
(c) π⁻p (360 GeV/c)
• π° Inclusive (Ref 4)
□ (π⁺+π⁻)/2 (This Expt)
(a)
(b)
(c)
E(dσ/d³p) (μb/GeV²)
p_T (GeV/c)

Fig. 1

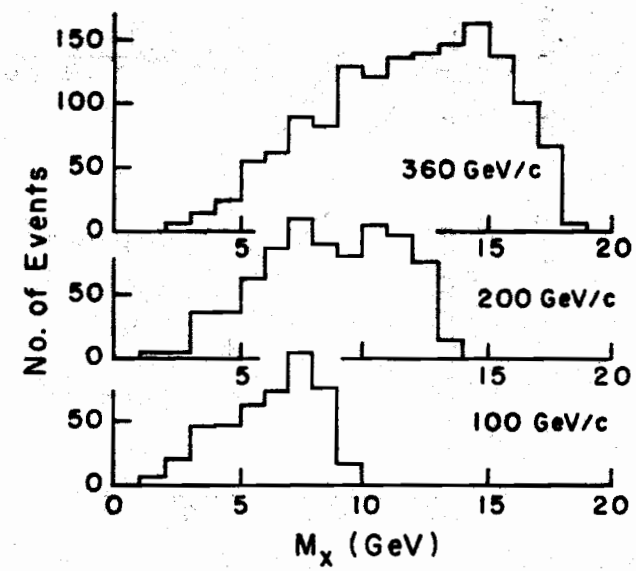
360 GeV/c
200 GeV/c
100 GeV/c
No. of Events
M_X (GeV)

Fig. 2

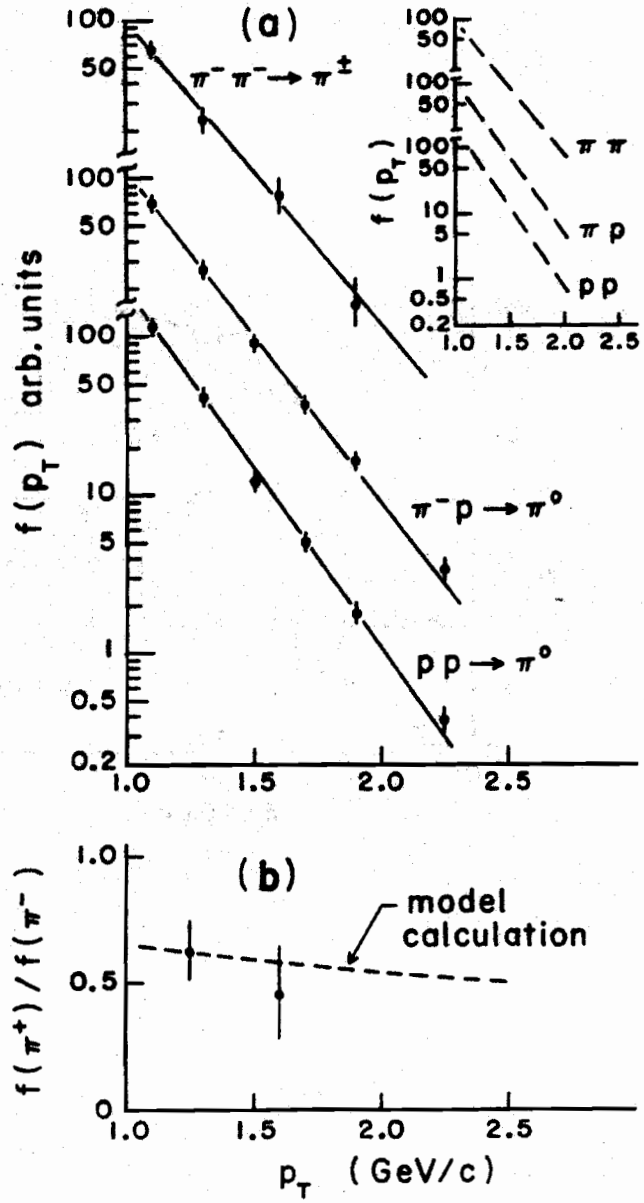
(a)
$\pi^- \pi^- \to \pi^\pm$
$\pi^- p \to \pi^0$
$p\,p \to \pi^0$
$\pi\,\pi$
$\pi\,p$
$p\,p$
$f(p_T)$ arb. units
(b)
model calculation
$f(\pi^+)/f(\pi^-)$
p_T (GeV/c)

Fig. 3