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ABSTRACT

We present measurements of the production of symmetric high mass hadron and pion pairs by protons of 200, 300 and 400 GeV, incident on a beryllium target. The two-particle invariant cross section for pion production can be described by a "scaling fit" $E_1E_2d^6\sigma/dp_1^3\,dp_2^3 = (1.7 \times 10^{-28})\ p_t^{-8.4}\ (1-x_t)^{14}\ cm^2/GeV^4$ (where p_t is the mean p_t of the two hadrons). This fit is of the same form as the scaling fits describing single pion inclusive production. Equality of the p_t dependence in the two processes is observed, confirming the role of smearing contributions to single hadron cross sections.

We have measured at Fermilab hadron pair and single hadron inclusive production by protons incident on a beryllium target, using a two arm magnetic spectrometer with Čerenkov particle identification. The hadrons were detected and identified over a 0.063 steradian solid angle (center of momentum system) centered about a rapidity $y_{cm} = 0.0$ for 400 GeV protons, $y_{cm} = 0.2$ for 300 GeV and $y_{cm} = 0.4$ for 200 GeV beam momentum. Details about the apparatus and analysis procedure can be found in earlier publications[1,2,3].

The large transverse momenta (p_t) observed[4] in single inclusive hadron production are now believed to arise from scattering of hard constituents within the colliding hadrons. Experimentally one finds[2,4,5,6] in the region $3 \leq p_t \leq 8$ GeV that single pion production is well described by a "scaling fit" of the form

$$\sigma_s \equiv E \frac{d^3\sigma}{dp^3} = A\, p_t^k\, (1-x_t)^b, \text{ where } x_t \equiv \frac{2p_t}{\sqrt{s}} \text{ and } k \cong -8. \quad (1)$$

Dimensional analysis suggests a dependence $\sigma_s \sim p_t^{-4}$, in contrast to the observed p_t^{-8} dependence. Theoretical efforts to reconcile the two values for the power k have resulted in two main types of explanation. The first[7], called the "constituent interchange model" (CIM) starts with a basic scattering process involving more than two constituents (e.g. a meson interacting with a quark) to arrive "naturally" at steeper p_t dependences.

The second effort[8,9,10] the "QCD parton model" (QPM) modifies the basic p_t^{-4} dependence with some well known and some more hypothetical corrections. These include "smearing" due to the initial transverse momentum (k_t) of the colliding constituents and scale breaking QCD effects.

Our measured invariant single pion inclusive production cross sections for π^+ and π^- production on beryllium are shown in Figs. 1a and 1b, together with data from the Chicago Princton (CP) group[6] and fits of the form (1) with the fit parameters as listed in Table I. Only data points above $x_t = 0.24$ have been included in the fit. Below this x_t value the data do not exhibit scaling. Although our data agree with the CP data[6] over our x_t range, we find that our fits prefer somewhat smaller b parameters than the fits of Ref. 6, while the k parameters are in agreement. This is due to the fact that there are still small scaling violations at the lower end of our fit x_t range, which affect the value of the b parameter (describing the shape of the cross section curves versus x_t). The k parameter, on the contrary, depends only on the ratio of the cross sections at a common x_t and can thus be determined without much sensitivity to b. The invariant $\pi^+\pi^-$ inclusive production cross sections σ_p are shown in Fig. 1c, where the lines represent the fit listed in Table I for those pairs. Only symmetric pairs with net $p_t' \equiv |\vec{p}_{t,1} + \vec{p}_{t,2}| < 1.1$ GeV have been included. In this range, the cross section depends very little on the net p_t' of the pair[2] and smearing effects due to internal quark motion are expected to be negligible[9].

The data described so far are from the reaction

$$p + \text{Be-nucleus} \longrightarrow \begin{pmatrix} \pi^+ \\ \pi^- \\ \pi^+\pi^- \end{pmatrix} + \text{anything}$$

Anomalous nuclear enhancement of single hadron production has been observed[5,6] at large p_t. We have published[3] measurements of the nuclear enhancement of large mass dihadron production. Using these studies it is possible to extrapolate the Be target data to cross sections "per nucleon" (which is roughly half proton, half neutron). Fits to nucleon cross sections are also presented in Table I. Since no significant nuclear enhancement was seen[3] in the production of high mass symmetric $\pi^+\pi^-$ or h^+h^- pairs, there are no separate entries for pair fit parameters per nucleon.

The shift in y acceptance with beam energy, mentioned above, could affect the determination of the power k if combined with a strong y-dependence of the cross sections. These cross sections are expected[10] to vary by only about 10%, however, over our range of 0.5 units of rapidity. We have verified, by comparing our angular distributions from Be and W targets, that also within 10% accuracy, no y-dependence of σ_p or σ_s is introduced by the nuclear targets. The determination of Δk (defined below) is sensitive only to the difference of the y distributions of single and pair cross sections. A 10% difference in cross section at 200 or 400 GeV only changes k by 0.3 units.

Table I lists results for unlike charged pion pairs ($\pi^+\pi^-$) and for all charged hadrons, regardless of identification (h^+, h^-). The CIM model is supposed capable of predicting the power k of p_t in symmetric pair production for all hadrons, but the calculation is still in progress[11]; in the QPM model, on the other hand, it is not known yet how to calculate baryon production. For these reasons we only compare the pion data to the QPM expectations. The quantity $\Delta k \equiv k_{\pi^+\pi^-} - 1/2\ (k_{\pi^+} + k_{\pi^-})$ is expected[9] to be approximately zero in the QPM model. Lack of smearing effects in the symmetric pair data is expected to compensate the dimensional differences between σ_p and σ_s. Note that Δk is insensitive to overall normalization errors. Systematic errors, except for the normalization errors, have been added to the statistical errors of the data points in quadrature. The effect of these systematic errors is, however, not fully reflected in the quoted fit errors since they are correlated for neighboring data points. We estimate the effect of the imperfect knowledge of efficiencies and normalizations to be 0.14, 0.18 and 0.12 of the cross sections for single hadrons, pairs and their ratio, in that order, corresponding to an error in k of 0.4, 0.5 and 0.4 units respectively. Together with the fit errors, we estimate the total error on k as ±0.5 units for single hadrons, ±0.6 units for pairs and ±0.5 units for the error of Δk.

We conclude then from Table I that $\Delta k = +0.2 \pm 0.5$ for the Be data, and $\Delta k = +0.5 \pm 0.5$ for the nucleon analysis. The data are therefore in agreement with $\Delta k = 0$ and with the expectations of the modified hard scattering model with internal parton k_t smearing. The QPM model[8,9] describes the p_t dependence of both our single pion and our pion pair data if the quark motion is taken to be of the magnitude deduced from the transverse momentum distribution of hadronically produced muon pairs[12]. In both this and the μ pair experiment the large value for $k_t \cong 1$ GeV may be due to either primordial quark motion, or to gluons participating in the scattering process, or both.

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R. D. Field, Phys. Rev. Lett. 40, 997 (1978).

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Our definition of the two particle invariant inclusive cross section differs from the one used in this reference by two powers of p_t; it also differs in dimension from

our definition of the inclusive single particle cross section. Note that the predictions in this reference have been obtained by integrating over the complete "away side" jet (all azimuth angles ϕ), while our measurements are of the differential cross sections near $\Delta\phi = 180^{\circ}$; also the c.m. rapidity y has been kept zero for the above calculations.

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TABLE I

FITS TO SINGLE HADRON AND SYMMETRIC PAIR INVARIANT CROSS SECTIONS

$$\sigma_s \equiv E\frac{d^3\sigma}{dp^3} \text{ or } \sigma_p \equiv E_1E_2\frac{d^6\sigma}{dp_1^3\,dp_2^3} = A(1-x_t)^b\,p_t^k \text{ where } x_t \doteq \frac{2p_t}{\sqrt{s}}$$

$$p_t \equiv \tfrac{1}{2}(p_{t,1}+p_{t,2}) \text{ for pairs}$$

Cross Section		A $\left(\frac{cm^2}{GeV^2} \text{ or } \frac{cm^2}{GeV^4}\right)$	b	k	χ^2/D.F.
Single π^+	(Be)	$(5.5\pm1.5)\times10^{-26}$	6.1±0.8	−8.9±0.2	18/17
	(AC)	$(7.2\pm1.9)\times10^{-27}$	6.1±0.8	−9.2±0.2	17/17
π^-	(Be)	$(4.7\pm1.4)\times10^{-26}$	8.1±0.8	−8.2±0.2	14/17
	(AC)	$(6.5\pm1.7)\times10^{-27}$	8.1±0.8	−8.6±0.3	14/17
h^+	(Be)	$(39.1\pm4.5)\times10^{-26}$	7.3±0.2	−9.5±0.1	54/33
h^-	(Be)	$(16.3\pm1.7)\times10^{-26}$	10.7±0.2	−8.4±0.1	38/33
Symmetric	$\pi^+\pi^-$	$(1.7\pm0.7)\times10^{-28}$	14.0±0.8	−8.4±0.2	16/29
(Be)	h^+h^-	$(8.4\pm1.9)\times10^{-28}$	13.7±0.6	−9.2±0.2	34/42

Fits are to data above $x_t = 0.24$.

Be = beryllium data, per Be-nucleus.

AC = A-dependence corrected, using $A^{\alpha(p_t)}$, with α from Ref.5,6; per nucleon.

Systematic errors are discussed in the text. The total error for k is estimated to be ±0.5 units for singles and ±0.6 units for pairs.
Note that the χ^2 values are affected by deviations from scaling at low x_t, as well as by the addition of systematic errors.

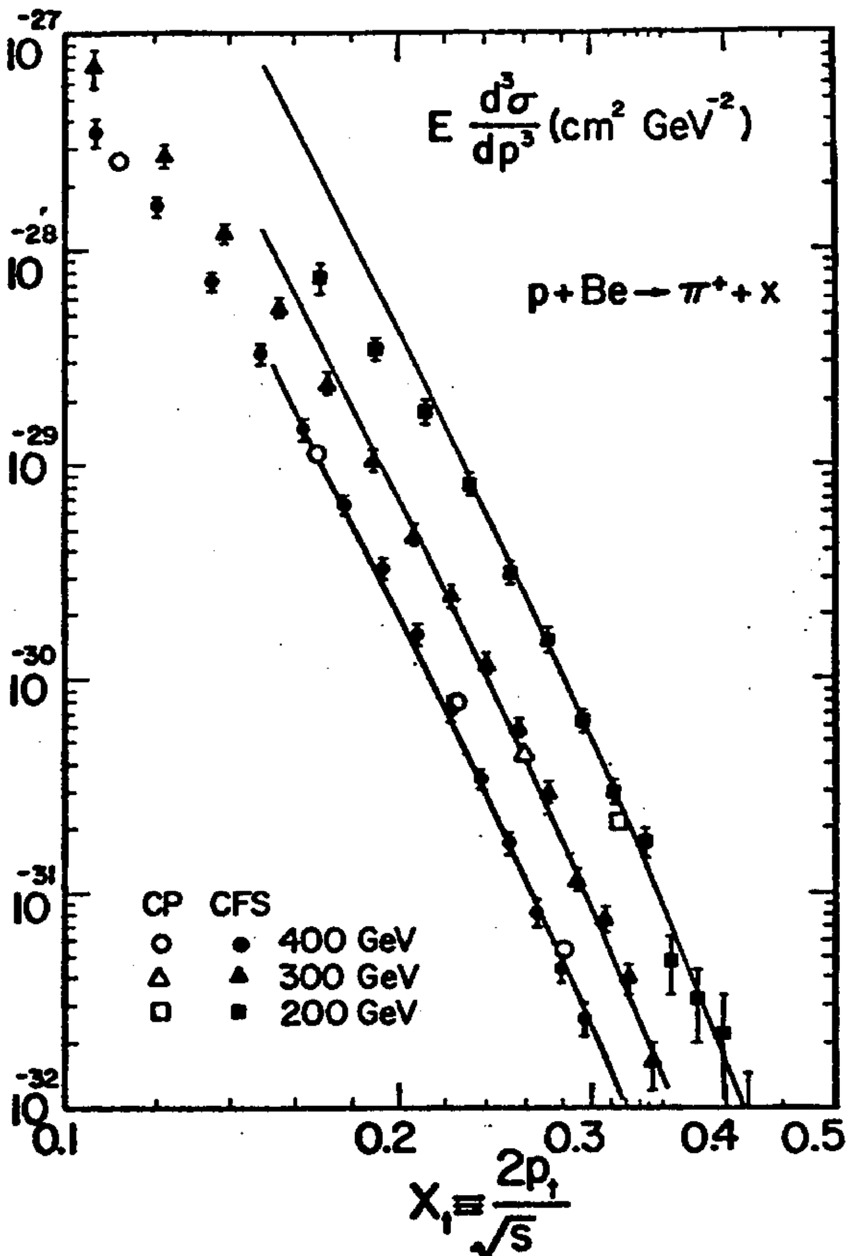

Fig. 1a. Invariant single π^+ inclusive production cross section per Be-nucleus for 200, 300 and 400 GeV protons. The lines represent the fit from Table I to data above x_t = 0.24. The open symbols are data points from the CP group.[6]

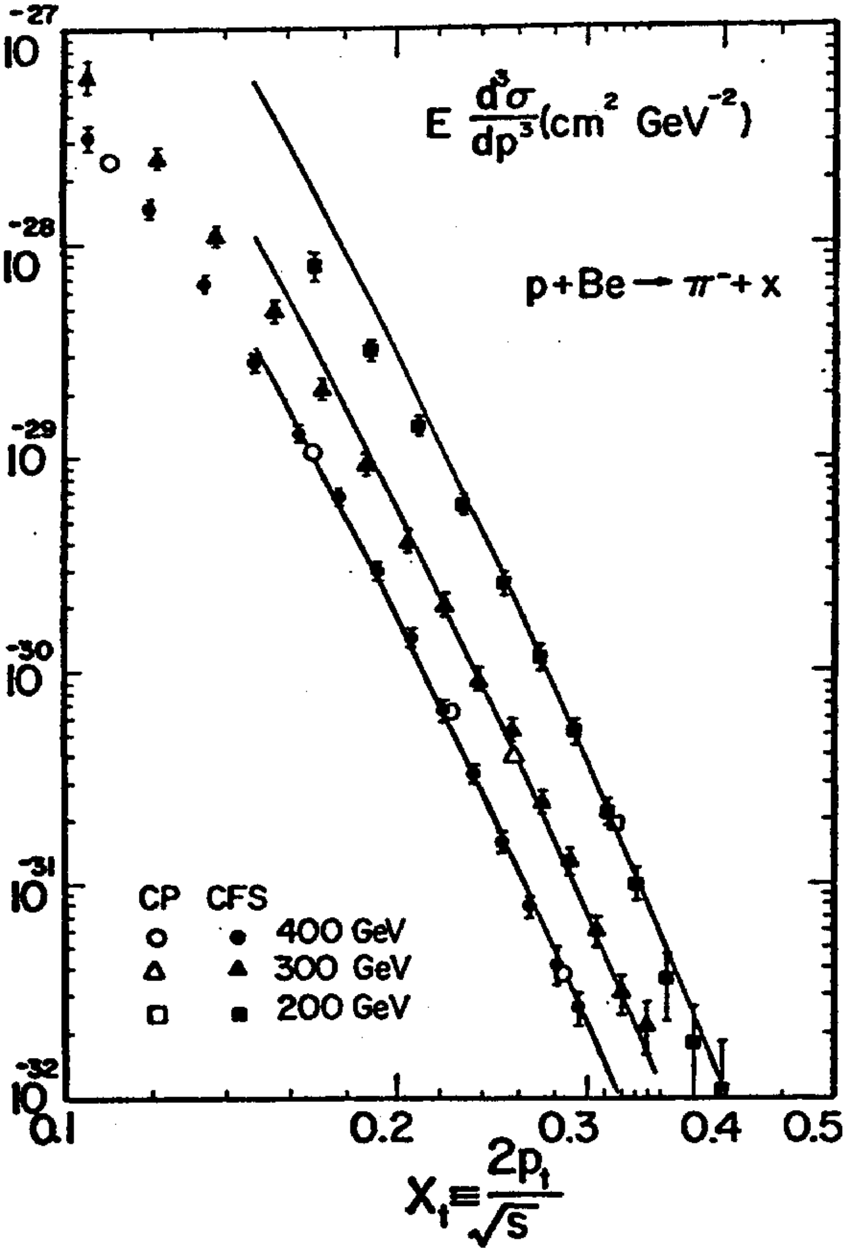

Fig. 1b. Same as Fig. 1a, but for negative pions.

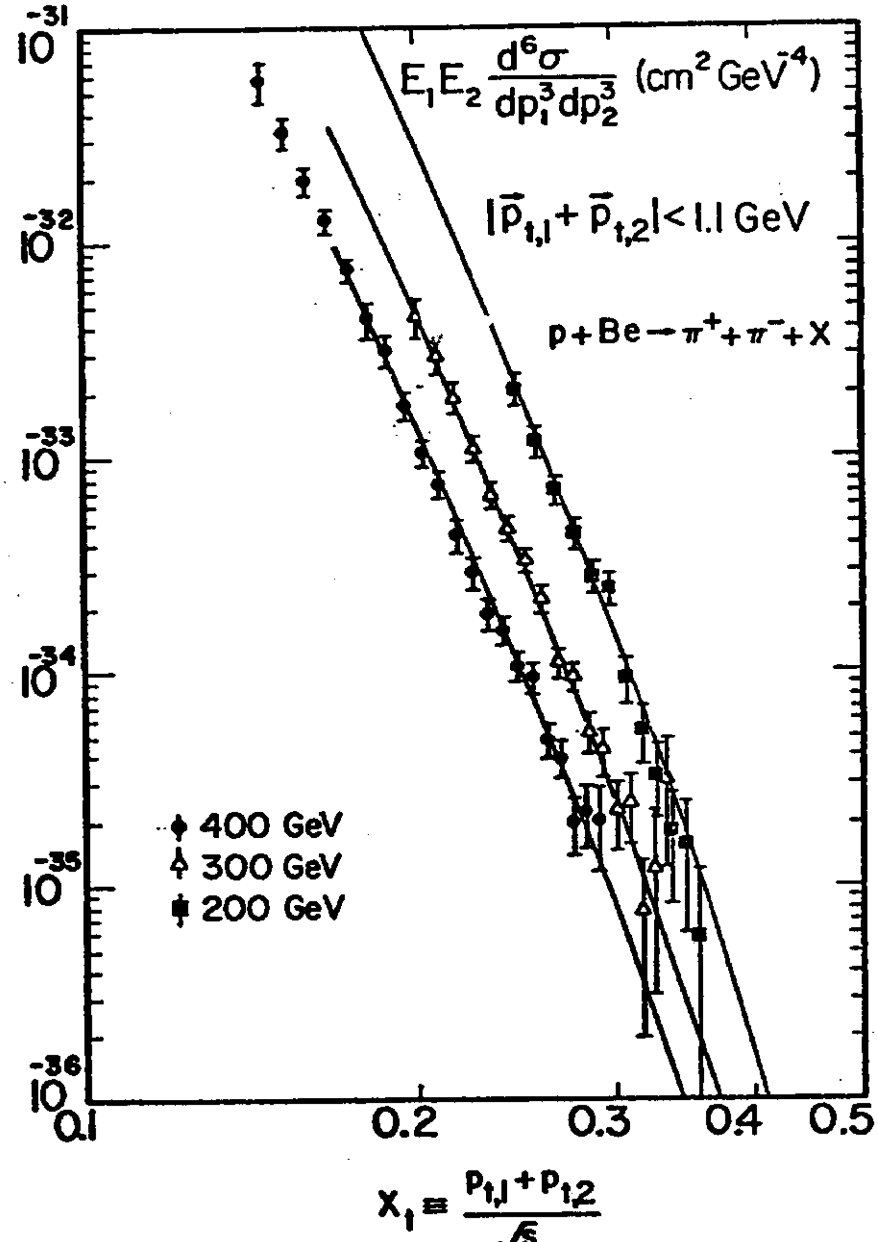

Fig. 1c. The two particle invariant cross section for $\pi^+\pi^-$ production by 200, 300 and 400 GeV protons, striking a Be target. The lines are the fit functions from Table I for data above $x_t = 0.24$.