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ABSTRACT

We have measured the invariant π^0 inclusive cross section in the reaction $p + p \to \pi^0 +$ anything for incident proton momenta from 50 to 400 GeV/c and lab angles of 80, 100, and 120 mrad. It is shown that in the range of $p_\perp = 0.3$ to 4.3 GeV/c, the cross section can be factorized into a product of two functions, one in $p_\perp$ and the other in a new scaling variable $x_R = p^* / p^*_{max}$.

The study of the production of pions with large transverse momentum, $p_\perp$, in proton-proton collisions is expected to give insight into the short distance structure of the proton.[1,2,3] Great interest in this field has been stimulated by the experimental results obtained at the CERN ISR[4,5,6] and at NAL.[7,8] The CCR group[4] at the ISR were the first to show that near 90 degrees in the pp center of mass system the large $p_\perp$ data were consistent with a scaling behavior with respect to the variable $x_\perp = 2p_\perp/\sqrt{s}$. On the other hand, it has been known for several years that the small $p_\perp$ single pion inclusive data exhibit scaling with respect to the variable $x_{\parallel} = 2p_{\parallel}^{*}/\sqrt{s}$ at all center of mass angles. In this experiment, data have been obtained on single π^0 inclusive spectra from 40^0 to 110^0 in the pp center of mass system and for 0.3 GeV/c $\leq p_\perp \leq 4.3$ GeV/c. It has been found that the cross sections scale when the "radial" variable $x_R = p^{*} / p^{*}_{max}$ is used. This new radial scaling variable, x_R, may be regarded as a generalization of the previous variables $x_\perp$ and $x_{\parallel}$. Clearly in the appropriate limits of small $p_\perp$, x_R tends to $x_{\parallel}$, while at small $p_{\parallel}^{*}$, x_R tends to $x_\perp$.

We have measured the photon energy spectrum in the process $p + p \rightarrow \gamma$ + anything for incident proton energies from 50 to 400 GeV. Data were accumulated at three laboratory angles, 80, 100, and 120 mrad, over a range in photon transverse momentum from 0.3 to about 4.3 GeV/c. Assuming that all the detected photons came from π^0 decay, the observed photon energy spectra were then converted into invariant π^0 cross sections using Sternheimer's[9] prescription.

The experiment was performed at the Internal Target Area at NAL using both a hydrogen gas jet[10] and a rotating carbon fiber target intercepting the accelerator's internal proton beam. The detection system[7] consisted of a lead-glass shower counter which was used to measure the gamma ray energy and scintillation counters which were used to separate incident gamma rays from hadrons and muons. Because the gamma ray opening angle in $\pi^0 \rightarrow 2\gamma$ decay was larger than the angular acceptance of the spectrometer, the detector was sensitive to only one of the two π^0 decay photons.

At each laboratory angle, the normalization of the γ cross sections, and hence the π^0 invariant cross sections, was determined from a short run using the hydrogen jet target, where a solid state detector was used to monitor the rate of recoil protons elastically scattered at small momentum transfer. Using the known[11,12] pp elastic cross section to determine the luminosity, the absolute gamma ray cross section was then obtained. The major portion of the data at each laboratory angle was taken using the rotating carbon fiber target. To establish that we were not sensitive to complex target effects, gamma ray data were collected at one laboratory angle with large and comparable statistics using both the carbon fiber and hydrogen jet targets. There was no observable difference in the shape of the gamma spectra from the two type of target.

Figure 1 displays the $p_\perp$ dependence of the π^0 invariant cross section for the data obtained at 80 mrad. At a fixed $p_\perp$, the cross section rises with increasing incident momentum; at $p_\perp$ = 2 GeV/c, there is roughly a factor of 25 between the cross sections at incident momenta of 50 and 250 GeV/c. Furthermore, the slope of the cross section at large $p_\perp$ decreases with increasing incident momentum.

The π^0 invariant cross section reveals a strikingly simple behavior when it is expressed in terms of certain variables. For the three lab angles 80, 100 and 120 mrad, we find that the invariant π^0 cross section is well represented by the product of two functions, $f(x_R)$ and $g(p_\perp)$, that is

$$E \frac{d^3\sigma}{dp^3} = f(x_R)\, g(p_\perp).$$

The variable $p_\perp$ is the familiar transverse momentum of the π^0 while the radial scaling variable x_R is the ratio of the π^0 momentum to the maximum momentum,

$$x_R \equiv p^* / p^*_{max} \cong 2p^* / \sqrt{s}.$$

For a particular lab angle, the data from this experiment cover a large range of x_R for fixed $p_\perp$ and thereby allow an accurate determination of the scaling function $f(x_R)$. By an iterative procedure, self-consistent solutions for the functions

$f(x_R)$ and $g(p_\perp)$ were obtained from the invariant π^0 cross sections . The resulting functions $f(x_R)$ and $g(p_\perp)$ for 80 mrad are shown in figs. 2 and 3.[13]

The degree to which the radial scaling function $f(x_R)$ is independent of the transverse momentum, $p_\perp$, for a particular lab angle can be seen in Fig. 2. This figure shows that $f(x_R)$ is, to a good approximation, a unique function of x_R, which demonstrates the validity of the factorization of the π^0 invariant cross section. The solid line of Fig. 2 is a constant times $(1 - x_R)^4$ and gives a convenient although rough description of the scaling function $f(x_R)$.

Having determined a unique $f(x_R)$, the transverse momentum function $g(p_\perp)$ for each incident momentum is computed as the invariant cross section at that momentum divided by $f(x_R)$. In Fig. 3, this result has been plotted for five different incident proton momenta from 50 to 250 GeV/c for the same lab angle, 80 mrad. It can be seen that $g(p_\perp)$ appears to be a universal function over six decades in magnitude, even though, as noted previously, the π^0 inclusive cross sections vary widely in shape and magnitude over this same range in $p_\perp$ and incident momentum. This implies that $g(p_\perp)$ has reached its asymptotic limit even at an incident momentum as low as 50 GeV/c. The solid line in Fig. 3 has the functional dependence $(p_\perp{}^2 + 0.86)^{-4.5}$ and fits the data well for $p_\perp > 0.5$ GeV/c.

The functions $f(x_R)$ and $g(p_\perp)$ were determined separately at each laboratory angle of 80, 100, and 120 mrad. The three radial scaling functions $f(x_R)$ and similarly the three intrinsic transverse momentum functions $g(p_\perp)$ were consistent with each other within the errors of the data.

In conclusion, from 40 to 110 degrees in the center of mass and from 50 to 400 GeV/c incident momenta, we have shown that:

a) The π^0 inclusive production cross section in pp collisions factorizes into a product of two functions, $f(x_R)$ and $g(p_\perp)$.

b) Both the radial scaling function, $f(x_R)$, where x_R is a new scaling variable, and the transverse momentum functión, $g(p_\perp)$, are universal functions over these kinematic ranges.

c) Approximate analytic expressions for these functions are

$$f(x_R) \propto (1 - x_R)^4$$

and

$$g(p_\perp) \propto (p_\perp^2 + 0.86)^{-4.5}.$$

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[13] The shape of the radial function, $f(x_R)$, is sensitive to errors in the energy dependence of our normalization to the pp elastic cross section and the energy calibration of our lead glass counter, especially near the phase space boundary $x_R = 1$. The absolute normalization of the data is reflected in the magnitude of the $p_\perp$ function.

FIGURE CAPTIONS

Fig. 1 Shown plotted versus $p_\perp$ are the invariant π^0 cross sections at θ_{lab} = 80 mrad for four incident proton momenta, 50.9, 105.9, 200.9, and 250.9 GeV/c.

Fig. 2 The functions $f(x_R)$ calculated for 12 fixed $p_\perp$ values for the 80 mrad data are compared with each other and with the functional form $(1 - x_R)^4$.

Fig. 3 The functions $g(p_\perp)$ calculated for four incident momenta at 80 mrad are compared with each other and with the functional form $(p_\perp{}^2 + 0.86)^{-4.5}$.

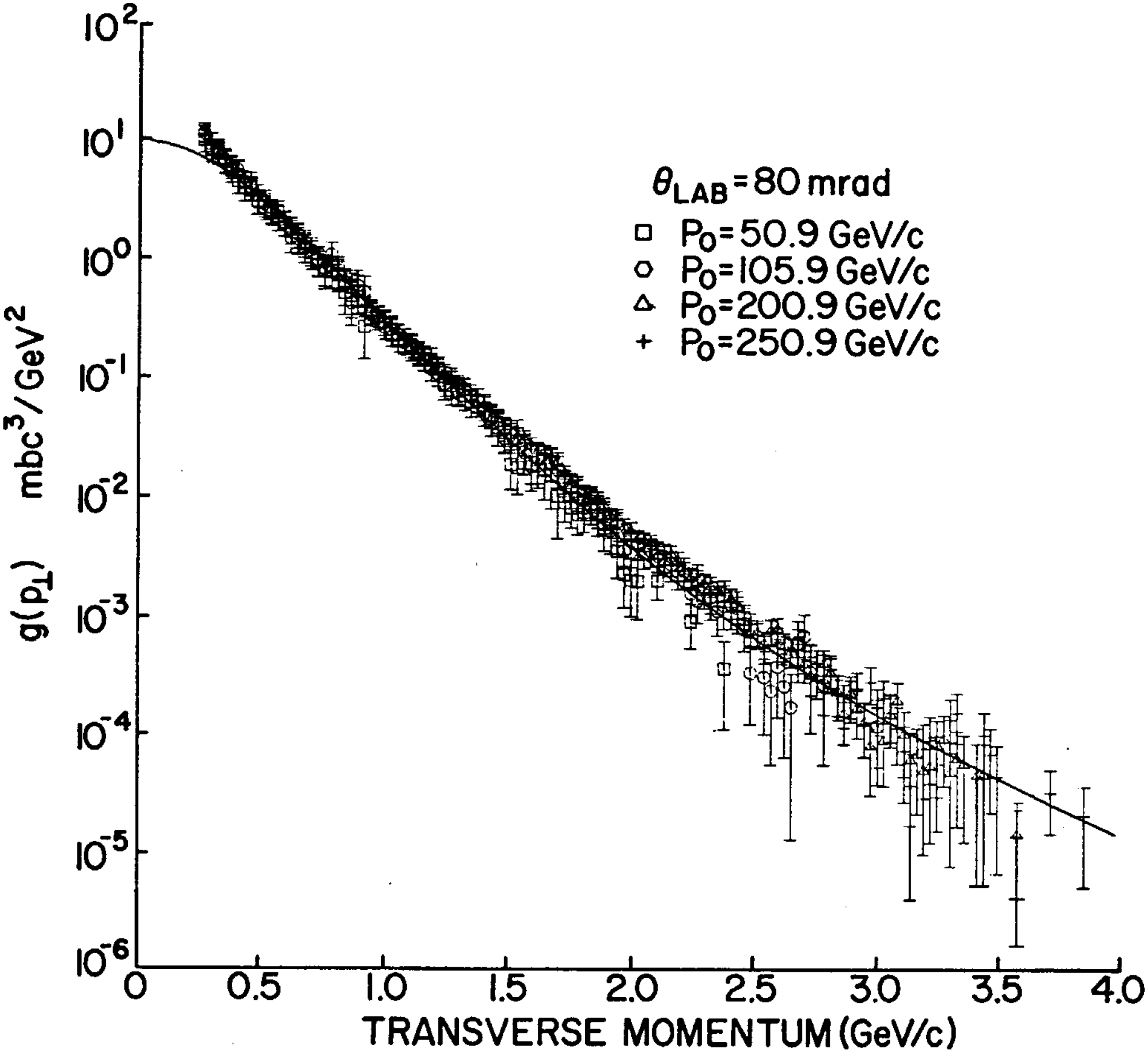
θ_{LAB} = 80 mrad
□ P_0 = 50.9 GeV/c
○ P_0 = 105.9 GeV/c
△ P_0 = 200.9 GeV/c
+ P_0 = 250.9 GeV/c
$g(p_\perp)$ mbc^3/GeV^2
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
TRANSVERSE MOMENTUM (GeV/c)

Fig. 3

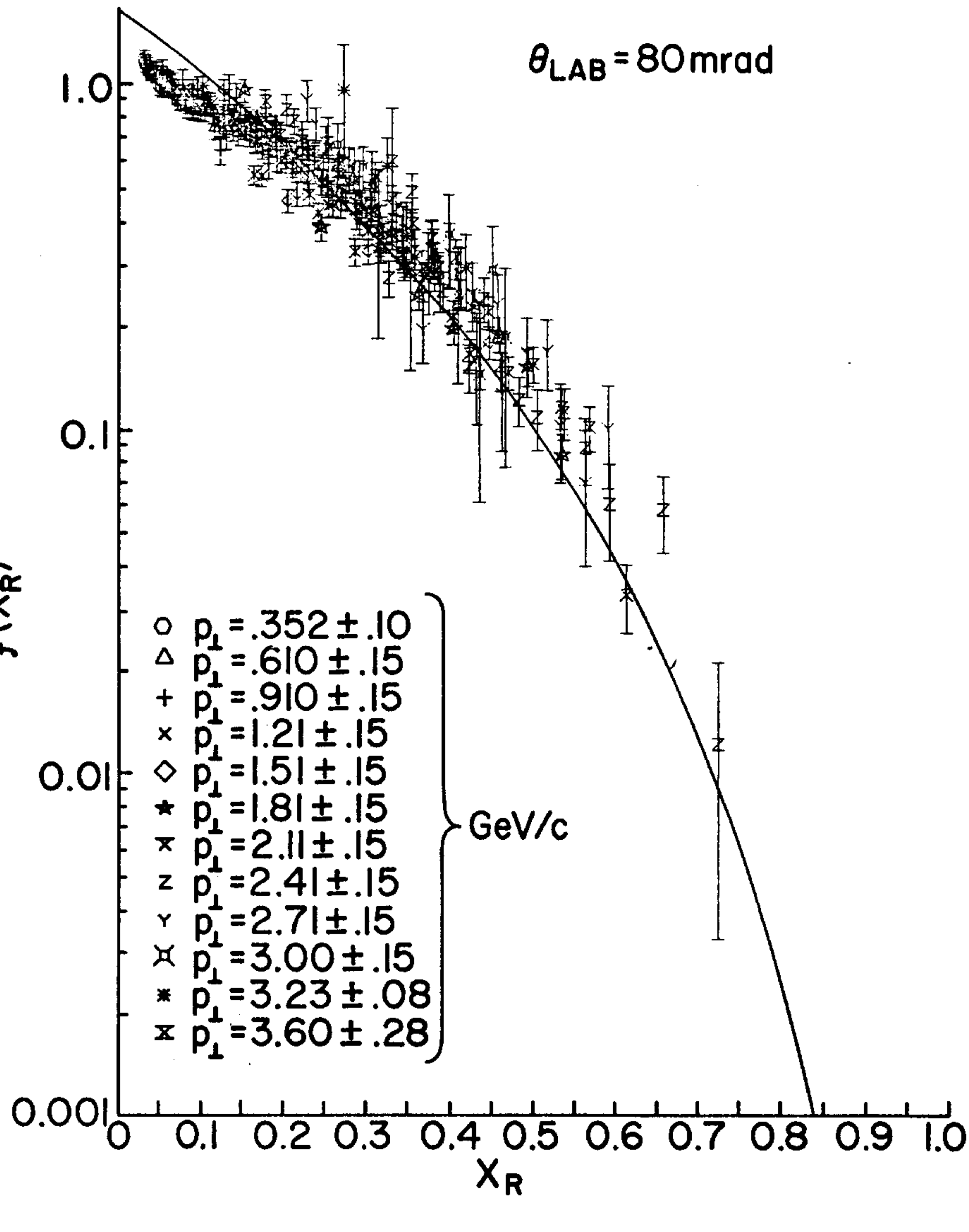
θLAB = 80 mrad
f(XR)
XR
1.0
0.1
0.01
0.001
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
p⊥ = .352 ± .10
p⊥ = .610 ± .15
p⊥ = .910 ± .15
p⊥ = 1.21 ± .15
p⊥ = 1.51 ± .15
p⊥ = 1.81 ± .15
p⊥ = 2.11 ± .15
p⊥ = 2.41 ± .15
p⊥ = 2.71 ± .15
p⊥ = 3.00 ± .15
p⊥ = 3.23 ± .08
p⊥ = 3.60 ± .28
GeV/c

Fig. 2