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ENERGY DEPENDENCE OF INCLUSIVE DISTRIBUTIONS IN PION-INDUCED REACTIONS*

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Abstract

We present data on the inclusive distributions $\pi^+ p \to \pi^\pm$ + anything and $\pi^- p \to \pi^-$ + anything at momenta from 3.7 to 18.5 GeV/c. Distributions are presented in the laboratory, center-of-mass, and projectile systems, and the approach to scaling is discussed.

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Recently, the question of scaling [1] in the inclusive reaction $a + b \rightarrow c$ + anything has been intensively discussed. Various tests [2] have been proposed suggesting the rate at which the scaling limit might be approached. Experimental data at more than one energy have been presented for the nonexotic reactions $\pi^- p \rightarrow \pi^-$ and $\gamma p \rightarrow \pi^-$ and the exotic reaction $pp \rightarrow \pi^-$ [3, 4]. (By "exotic" we mean that no resonances are known to decay into $ab\bar{c}$.)

The purpose of this letter is to present a systematic study of experimental results for pion-induced reactions and to consider their implications for our understanding of the nature of particle-production processes. We present data on the reactions

$$\pi^+ p \rightarrow \pi^+ + \text{anything} \qquad (1)$$

$$\pi^+ p \rightarrow \pi^- + \text{anything} \qquad (2)$$

and

$$\pi^- p \rightarrow \pi^- + \text{anything} \qquad (3)$$

with incident momenta from 3.7 to 18.5 GeV/c. These data have led us to several interesting results:

(1) By simultaneously studying data for the nonexotic reactions (1) and (3), and for the exotic reaction (2), we draw qualitative conclusions about the validity of some of the tests for scaling over this energy range.

(2) By comparing data from a quite low incident momentum -- 3.7 GeV/c -- where detailed studies have been made of the dominating quasi-two-body processes, to a quite high momentum -- 18.5 GeV/c -- where the high-multiplicity events are more important, we study the transition from the low-to-high-energy regimes.

(3) By studying data in the center-of-mass (c.m.), laboratory, and projectile systems, we observe in some detail the approach to scaling in each of three kinematical regions -- (a) pionization, (b) target fragmentation, and (c) projectile fragmentation.

(4) By looking at some of the specific exclusive processes, we observe which ones are contributing to the various kinematical regions.

(5) By comparing reactions (1) and (3), we observe the effects of charge symmetry on distributions.

Our new data sample consists of 110 000 $\pi^+ p$ interactions at 3.7 GeV/c* and 156 000 $\pi^+ p$ interactions at 7 GeV/c.† These data are compared with previous data [3] from $\pi^+ p$ interactions at 18.5 GeV/c and $\pi^- p$ interactions at 8.05 and 18.5 GeV/c.‡ We estimate that the contaminations in all these samples are very small.# The absolute

*The 3.7 GeV/c $\pi^+ p$ interactions were obtained from an exposure of the Berkeley (LBL) 72-inch HBC by the Trilling-Goldhaber group. All event types other than two-prongs were measured in all the film, and the two-prongs were measured in one-third of the film. Kinematic fits, including missing-mass hypotheses were attempted for each event; about 70% of the events had a kinematically constrained fit while 30% had only a missing-mass fit. The beam was contaminated with about 7% protons. The contamination was removed by subtracting an appropriate sample of events from highly contaminated film. Fits of the four prongs in each sample to both incident protons and π^+ were used to normalize the data. The subtraction was found to be important for two-prongs only. For further details, see ref. 5

†The data at 7 GeV/c came from a subsample of a large exposure of the SLAC 82-inch HBC obtained by Berkeley Group A. All events were measured and a kinematic analysis of each event was made (about 60% of the events had a kinematically-constrained fit and 40% had only missing-mass fits).

‡A total of approximately 10^5, 5×10^4, and 10^5 negative tracks from 18.5 GeV/c $\pi^+ p$, 8.05 GeV/c $\pi^- p$, and 18.5 GeV/c $\pi^- p$ interactions, respectively, were obtained from exposures of the Brookhaven 80-inch HBC by the Notre Dame Group. Only the negative tracks were measured, so momenta are not kinematically constrained. Separate measurements have been made of complete 4-prong events.

#For both the Berkeley samples, bubble-density information was used. We estimate that the contamination of $\pi^\pm$ by $K^\pm$ is negligible and the contamination of π^+ by protons is negligible except in the forward direction where it might be as high as a few percent. In the Notre Dame data all negative tracks are assumed to be π^-; the nonpionic contamination is estimated from a study of K^+K^- production in four-prong events to be at most a few percent (see ref. 3).

cross sections at 3.7 and 7 GeV/c were found by normalizing the number of events in each sample to previously measured total cross sections [6].

In fig. 1a are shown the distributions of the invariant structure function

$$F(x) = \int \frac{1}{\sigma_T} \frac{2E}{\pi\sqrt{s}} \frac{\partial^2\sigma}{\partial x \partial p_\perp^2} dp_\perp^2$$

in the c.m. for reactions (1), (2), and (3) as a function of the Feynman scaling variable $x = 2p_{\parallel}/\sqrt{s}$ (where E, $p_{\parallel}$, and $p_\perp$ are, respectively, the energy, longitudinal momentum, and transverse momentum of the pion in the c.m. of the reaction; $\sqrt{s}$ is the total c.m. energy of the reaction; and σ_T is the total cross section at large energy□. One expects[1] that at very high energies the quantity F(x) will be independent of s for each reaction and at x = 0 will be independent of the nature of the incident particle. Hence we can observe the rates at which these limits are approached at present accelerator energies.

We shall discuss first the reaction $\pi^+p \to \pi^- +$ anything. We observe that at x = 0 the distribution rises markedly with energy. At $x \sim \pm 1$, systematic behavior in the distribution is obscured because the kinematical limits of x depend on the total c.m. energy and the number of final-state particles. These kinematical regions are best studied in the laboratory and projectile systems.

For the reaction $\pi^+p \to \pi^+ +$ anything, we observe for $0 < x < 0.3$ an independence of energy from 3.7 to 7.0 GeV/c. At $x > 0.5$ there is a marked decrease in the π^+ distribution as s increases.

In fig. 1a we also observe that the π^- distributions from reaction (3) at 8.05 and 18.5 GeV/c are almost identical to the π^+ distribution of

□ The values of σ_T used were 23.4 mb for π^+p and 24.9 mb for π^-p.

reaction (1) for $+0.1 < x < +0.4$. Also the π^+ distribution of reaction (1) at 7 GeV/c agrees with the π^- distribution of reaction (3) at 8.05 GeV/c for x values extending to $x \sim +0.9$; i.e. the fast pions behave in a charge-in dependent way. At negative x the π^- distribution from reaction (3) approaches that from reaction (2); here, for both reactions, the target proton fragments into π^- in a similar way, approximately independent of the incident charge.

The energy dependence of these distributions can be qualitatively understood from studies of contributions from the various exclusive reactions and from different multiplicities. For example, at 3.7 GeV/c about half the cross section consists of two-prong inelastic events. These processes dominate π^+ production at $x \gtrsim +0.5$ in reaction (1). Processes involving π^- production ($\geq$ four-prongs) account for the remaining inelastic cross section. As s increases, there is a rapid decrease in the two-prong cross section and simultaneously an increase in the higher-multiplicity reactions, for which the pion distributions are strongly peaked near x = 0. These effects produce the fall in π^+ production for $x \gtrsim +0.5$ and relatively constant π^+ production at x = 0 for reaction (1), and an increase in π^- production near x = 0 for reaction (2). Similar arguments apply for the decrease in π^- production at $x \gtrsim +0.5$ in reaction (3). Thus, while the total cross section remains approximately constant, processes leading to the production of pions having the same charge as the incident pion are decreasing relative to processes yielding pions of the opposite charge.

At asymptotic energies, we might expect the pionization products near x = 0 to become independent of the charge of the incident pion. To study this, we plot in fig. 1b the structure function F(0) (averaged over $-0.02 < x < +0.02$) as a function of $s^{-1/4}$ §, as suggested by Abarbanel [7]. The data suggest that the distributions from the three reactions may indeed converge to the same value at very large energies.

A central question over the last few months has been the rate at which the proton fragmentation will approach the conjectured scaling limit. To investigate this, we have looked at all three reactions in the laboratory system, plotting the structure function

$$G(p_{\parallel}) = \int \frac{E}{\sigma_T} \frac{\partial^2\sigma}{\partial p_{\parallel} \partial p_{\perp}^2} dp_{\perp}^2$$ where all quantities are now evaluated in the laboratory system.

We observe in fig. 2a that for the reaction $\pi^+ p \to \pi^-$ in the region $-0.1 < p_{\parallel} < +0.2$ there is excellent agreement among the data at all three energies; for $p_{\parallel} < -0.1$ GeV/c a small decrease with increasing s; and for $p_{\parallel} > +0.2$ GeV/c an increase with s. (This latter effect has already been discussed in terms of the c. m. system near $x = 0$.) For the reaction $\pi^+ p \to \pi^+$ we note a marked decrease in the distribution with increased s in the momentum region from -0.3 to +0.4 GeV/c. We have found that a large contribution to the π^+ production in this region arises from the formation and decay of $\Delta^{++}(1236)$, a process which has a smaller cross section at 7.0 GeV/c than at 3.7 GeV/c.

The inclusive analysis of Mueller [8] suggests that the distribution $G(p_{\parallel})$ should approach the scaling limit as $A(p_{\parallel}) + B(p_{\parallel}) s^{-1/2}$ **. In fig. 2b we plot integrals of the distributions for $p_{\parallel} < 0$ as a function of $s^{-1/2}$ for each of the three reactions. We observe a rapid fall in

§ The inclusive distribution contains nonscaling terms that depend on $s^{-1/2}$ and $s^{-1/4}$. At $x \sim 0$ the $s^{-1/4}$ terms should dominate at very large energy, although at accelerator energies the $s^{-1/2}$ term could be significant. The present data are unable to distinguish between $s^{-1/2}$ and $s^{-1/4}$ dependence.

** In the laboratory system, terms in the distribution of order $s^{-1/4}$ are negligible for small $p_{\parallel}$. The $\pi^+ p \to \pi^-$ distributions of fig. 2a suggest that the function $B(p_{\parallel})$ has a zero in the region -0.1 GeV/c $< p_{\parallel} < +0.2$ GeV/c.

the cross section for the nonexotic reactions $\pi^+ p \to \pi^+$ and $\pi^- p \to \pi^-$. As might be expected, the cross section for π^+ production in proton fragmentation is much larger than the cross section for π^- production but the difference decreases as s increases. The decrease in $\pi^- p \to \pi^-$ is consistent with an approach to the cross section for $\pi^+ p \to \pi^-$ at higher energies as suggested by the factorization hypothesis[8]. The data for the exotic reaction $\pi^+ p \to \pi^-$ are consistent with the conjecture that the structure function is independent of s. However, the data are also consistent with a small decrease as s increases, suggesting that, while the structure function is close to its scaling limit, that limit has not quite been reached.

Finally, we consider the distribution $G(p_{\parallel})$ evaluated in the projectile system. This is of interest because here we are looking at the fragmentation of the incident pion. Because of scanning biases †† in the two-prong events, we show only the data for $\pi^+ p \to \pi^-$ in fig. 3. We observe that the data at 3.7 and 7.0 GeV/c agree (perhaps fortuitously) in the region $0 < p_{\parallel} < 0.8$ GeV/c, while the 18.5 GeV/c data are systematically lower in this region ‡‡. The values of the distributions integrated over $p_{\parallel} \leq 0.4$ GeV/c reflect this behavior. (See insert in Fig. 3.)

Recent data of Beaupre et al. [4], who reported on reactions (1) and (2) at 8 and 16 GeV/c, show similar trends in the F(x) distribution

†† During scanning of 3.7- and 7.0-GeV/c π^+ film, two-prong events with short proton recoils were not recorded. This causes a large depletion of events, primarily elastic scattering events, that have high-momentum forward-going π^+'s. Similar losses occur for the data of reaction (3).

‡‡ Some, but not all, of the decrease at 18.5 GeV/c may be a systematic experimental effect due to difficulties in reconstructing tracks of very high momenta.

although our distributions at comparable energies are about 10% higher. In the laboratory frame Beaupre et al. report excellent agreement in the integrated distribution $\int_{-0.4}^{0} G(p_{\parallel})\, dp_{\parallel}$. This observation is consistent with our data although the possibility of a small energy variation still exists.

In conclusion, the present analysis has displayed many interesting features of inclusive spectra in pion-induced reactions at present accelerator energies. We find that in the laboratory system, the distribution of the structure function $G(p_{\parallel})$ for the slowly-moving particles appears to be at, or close to, the scaling limit for the exotic reaction (2) but far from it for the nonexotic reactions (1) and (3). In the c. m. system, we observe charge symmetry for $x > +0.1$ in $F(x)$ for the nonexotic reactions at similar incident momenta, i. e., π^+ at 7 GeV/c and π^- at 8 GeV/c. In the region $x > +0.5$, there is a decrease with energy in each reaction due to the decrease in the cross sections of elastic and quasi-two-body processes. Near, $x = 0$, the pionization region, we observe a rapid increase in the distribution $F(x)$ for the exotic reaction (2) with increasing s. This effect is due to the increase of higher-multiplicity processes that produce pions near $x = 0$ because of kinematic restrictions. Although we see negligible change with s in the nonexotic reactions, the fact that the reactions $\pi^+ p \rightarrow \pi^+$ and $\pi^- p \rightarrow \pi^-$ are not equal suggests that we are far from the true scaling limit.

Acknowledgments

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Figure Captions

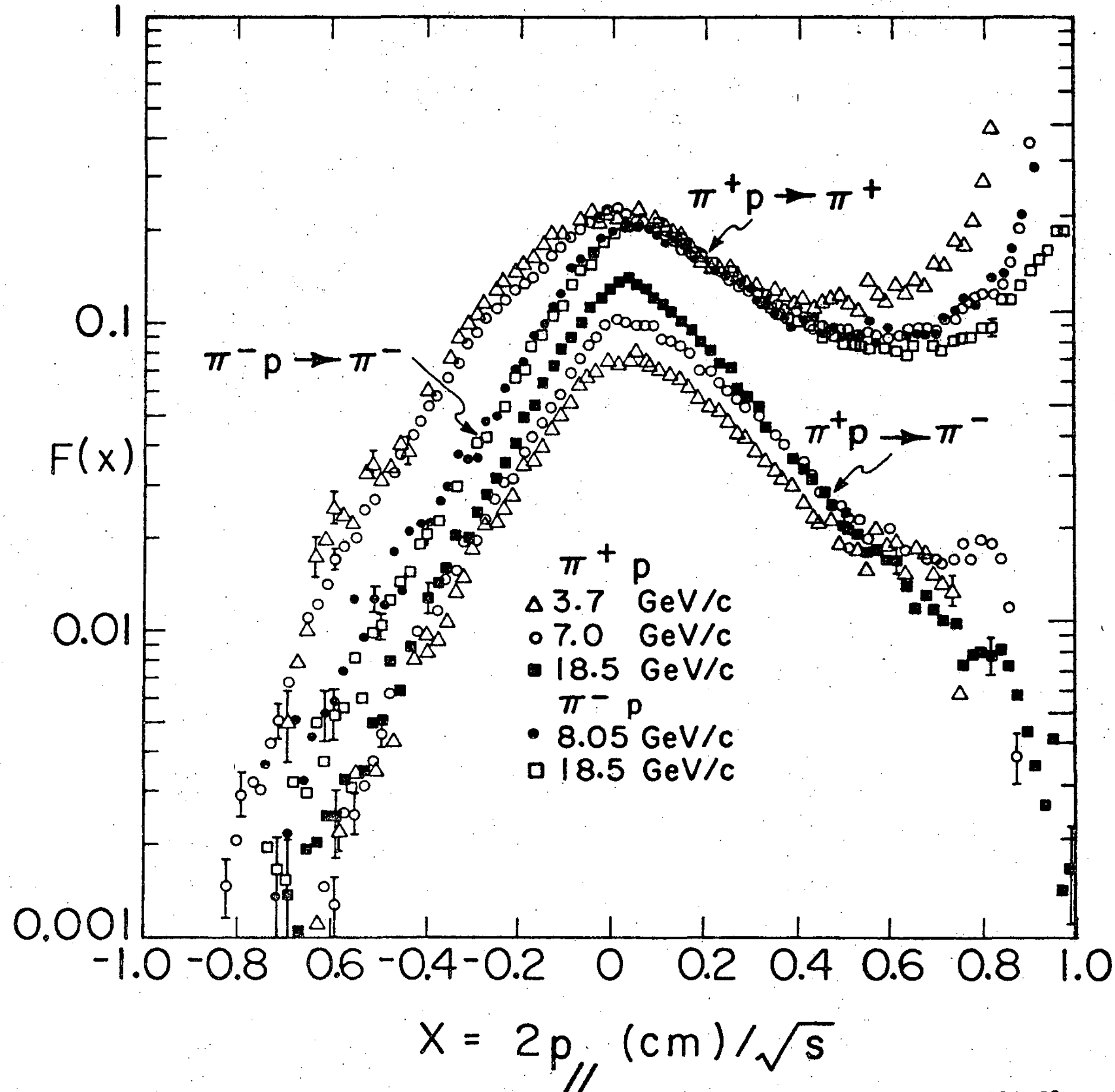
Fig. 1a. The inclusive structure function F(x) in the c. m. system (for definition see text) as a function of x. The errors shown are statistical only. The data points are for $\pi^+ p$ at 3.7, 7.0, and 18.5 GeV/c and for $\pi^- p \to \pi^-$ + anything at 8 and 18.5 GeV/c.

Fig. 1b. F(0) as a function of $s^{-1/4}$. Errors include systematics. The data point for $\pi^- p \to \pi^-$ at 24.5 GeV/c is from ref. 3.

Fig. 2a. The inclusive structure function $G(p_{||})$ in the laboratory system (for definition see text) as a function of $p_{||}$ (lab). The errors shown are statistical only.

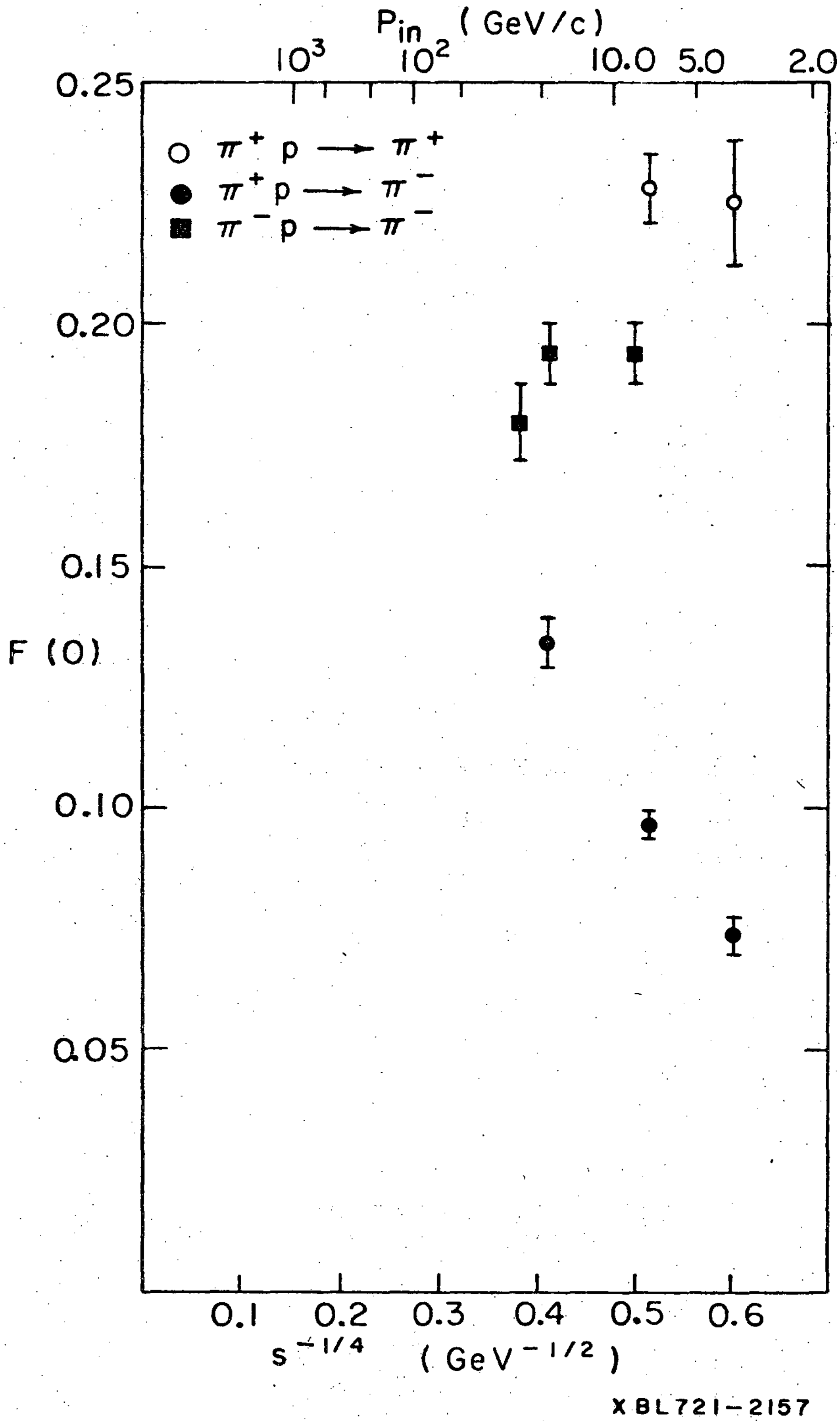
Fig. 2b. $\int_{-0.4}^{0} G(p_{||})\, dp_{||}$ as a function of $s^{-1/2}$. Errors include systematics. The point for $\pi^- p \to \pi^-$ at 24.5 GeV/c is from ref. 3.

Fig. 3. The inclusive structure function $G(p_{||})$ in the projectile system as a function of $p_{||}$ (projectile). The table shows the integral of the distribution for $0 < p_{||} < 0.4$ GeV/c. The error at 18.5 GeV/c does not reflect the difficulties in reconstructing tracks of very high momenta (see footnote ‡‡)



XBL 721-93

Fig. 1a



P_{in} (GeV/c)
10^3
10^2
10.0
5.0
2.0
0.25
0.20
0.15
0.10
0.05
F (0)
$\pi^+ p \to \pi^+$
$\pi^+ p \to \pi^-$
$\pi^- p \to \pi^-$
0.1
0.2
0.3
0.4
0.5
0.6
$s^{-1/4}$ ($GeV^{-1/2}$)
XBL721-2157

Fig. 1b

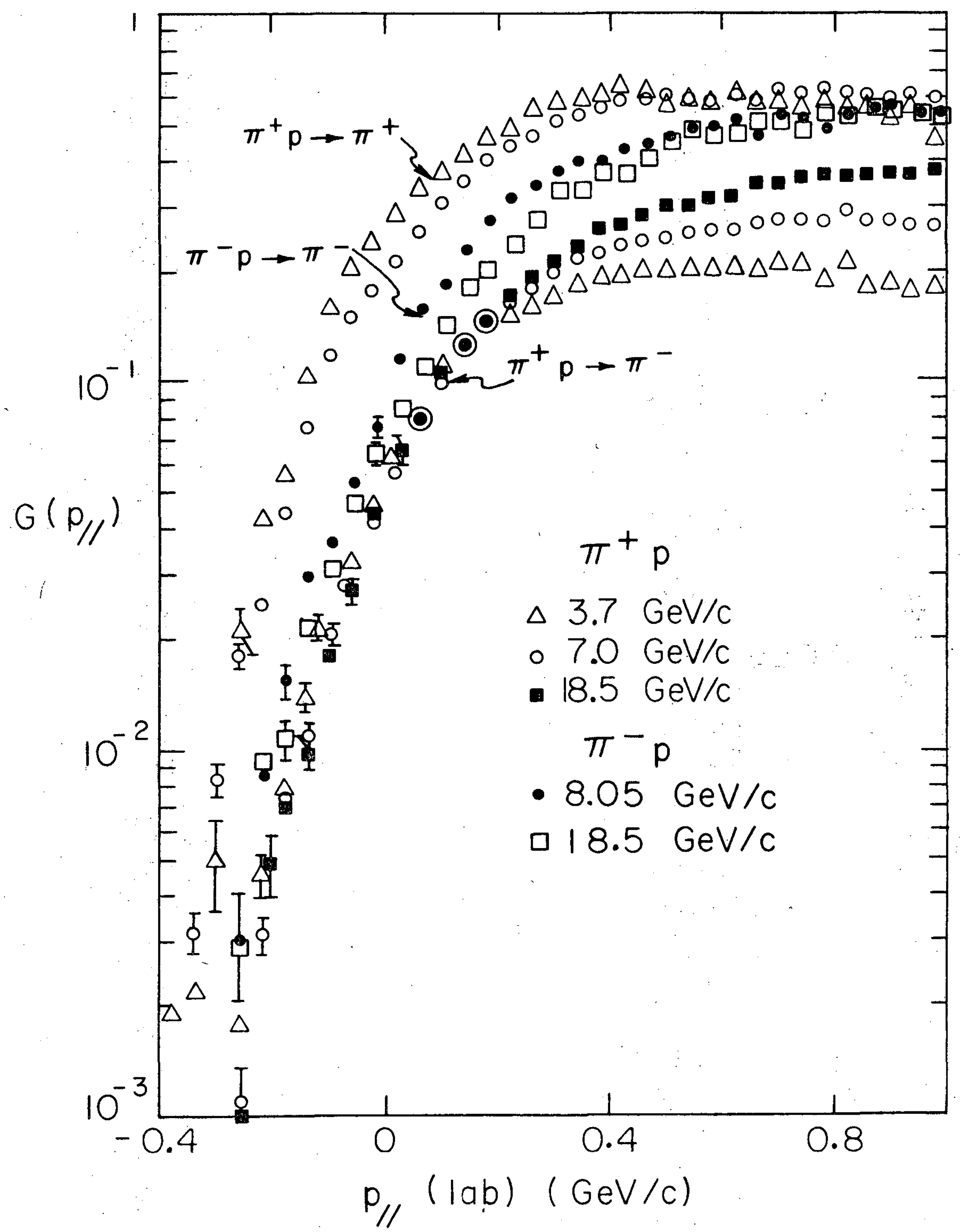
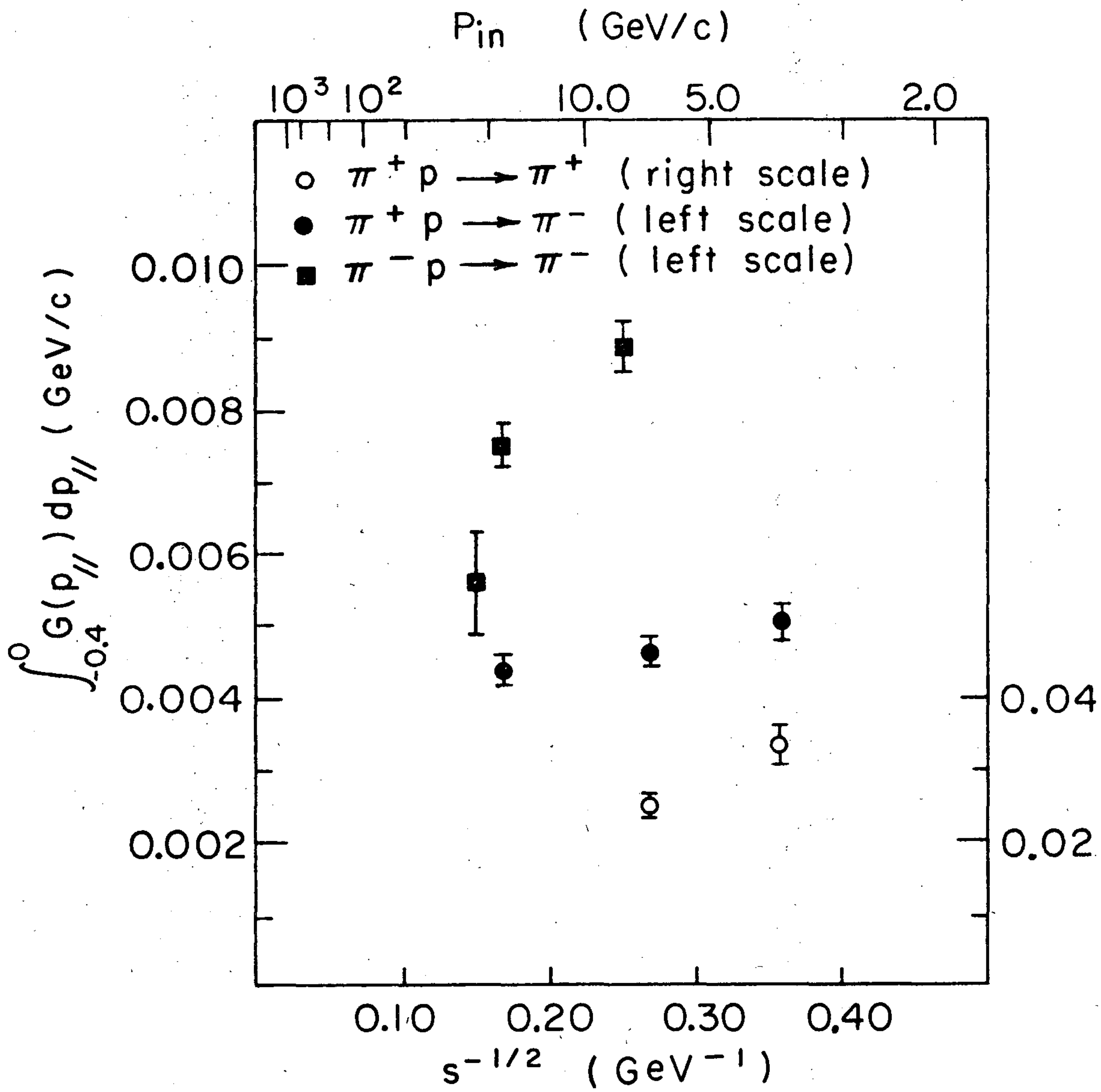

1
10⁻¹
10⁻²
10⁻³
G(p//)
-0.4
0
0.4
0.8
p// (lab) (GeV/c)
π⁺p → π⁺
π⁻p → π⁻
π⁺p → π⁻
π⁺p
3.7 GeV/c
7.0 GeV/c
18.5 GeV/c
π⁻p
8.05 GeV/c
18.5 GeV/c
XBL721-2100

Fig. 2a



XBL721-2158

Fig. 2b

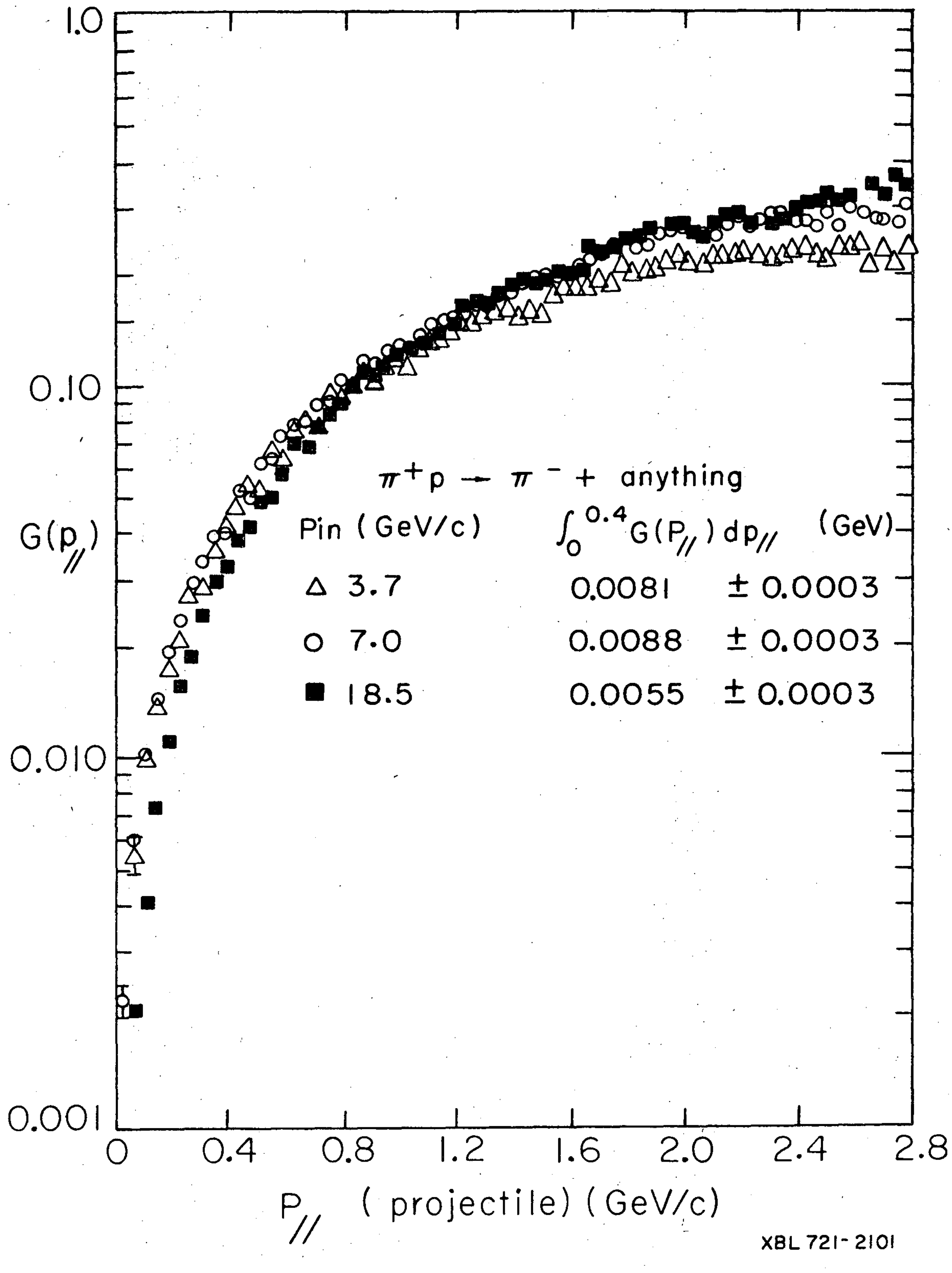

1.0
0.10
0.010
0.001
G(p//)
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
P// (projectile) (GeV/c)
π+p → π− + anything
Pin (GeV/c)
∫0 0.4 G(P//) dp// (GeV)
△ 3.7 0.0081 ± 0.0003
○ 7.0 0.0088 ± 0.0003
■ 18.5 0.0055 ± 0.0003
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Fig. 3

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