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Energy Dependence of Inclusive Distributions in Pion Induced Reactions

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In this talk I will present a systematic study of experimental results from pion induced reactions at incident momentum from 3.7 to 18.5 GeV/c. This work is a collaboration between physicists at the Lawrence Berkeley Laboratory and the University of Notre Dame.[1]

The data are from the reactions

$$\pi^+ p \to \pi^+ + \text{anything} \tag{1}$$

$$\pi^+ p \to \pi^- + \text{anything} \tag{2}$$

and $$\pi^- p \to \pi^- + \text{anything} \tag{3}$$

The data sample consists of 110 000 $\pi^+ p$ interactions at 3.7 GeV/c obtained from an exposure of the LBL 72-inch hydrogen bubble chamber by the LBL Trilling-Goldhaber group and 156 000 $\pi^+ p$ interactions at 7.0 GeV/c which are a subsample of a large exposure of the SLAC 82-inch H.B.C. obtained by LBL Group A. These new data are compared with previously published data for $\pi^+ p \to \pi^-$ at 18.5 GeV/c and $\pi^- p \to \pi^-$ at 8.05 and 18.5 GeV/c obtained by the Notre Dame group using the BNL 80-inch HBC.[2] We estimate that the contaminations in all samples is very small and that the absolute cross-sections are known to a few per cent.

Even though our energy range is rather low we have obtained several interesting results from these data:

(1) By simultaneously studying data for the non-exotic reactions (1) and (3) and 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 the 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, laboratory and projectile systems, we observe in some detail the approach to scaling in each of three kinematical regions -- (a) pionization region, (b) target fragmentation region, and (c) projectile fragmentation region.

(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 symmetries on distributions.

In Figure 1 are shown the inclusive distributions of the invariant structure function

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

in the c.m. for reactions (1), (2), and (3) as a function of the Feynman variable $x = 2p_{//} / \sqrt{s}$, where E, $p_{//}$ and $p_\perp$ are the energy, longitudinal momentum and transverse momentum of the pion in the center of mass 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. (The values 23.4 mb for π^+p and 24.9 mb for π^-p were used.) One expects that at very high energies this quantity will be independent of s for each reaction and at x = 0 will be independent of the nature of the incident particles.[3] Hence we can observe the rates at which these limits are approached at present accelerator energies.

We 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 Figure 1 we also observe that the π^- distribution from reaction (3) at 8.05 and 18.5 GeV/c are almost identical to the π^+ distribution of 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 up to ± 0.9; i.e. the fast pions behave in a <u>charge independent way</u>. At negative x the π^- distribution from reaction (3) decreases with increased s approaching that from reaction (2).

The energy dependence of these distributions can be qualitatively understood from studies of contributions from the various exclusive reactions and from different multiplicities. In figure 2 we show $\sigma_T F(x)$ for events of different topologies in reactions (1) and (2) at 3.7 and 7.0 GeV/c incident momenta. We see in Fig. 2a that at 3.7 GeV/c more than half of the cross-section consists of 2-prong events; the elastic events produce the sharp peak in the forward direction and the inelastic 2-prong events dominate π^+ production for $x > 0.4$. The 4-prongs contribute more than half of the π^+ distribution near $x = 0$ and show a bump in the forward direction due to π^+ from the decay of ρ^0's produced in the peripheral quasi-two-body reaction $\Delta^{++}\rho^0$. The contribution to the

π^+ spectrum from 6 prongs is quite small but is strongly peaked near $x = 0$ because of kinematic limitations. Turning to the π^- distribution (Fig. 2b) we see that the 4 prongs dominate for all x regions at this energy. As the incident momentum increases to 7 GeV/c (Fig. 2c and d) the 2-prong cross-section decreases rapidly; the 4-prong cross-section remains nearly constant, and the multiprong cross-section ($\geqslant$ 6 prongs) rises rapidly. These effects produce the fall in π^+ production for $x > 0.5$, relatively constant π^+ production near $x = 0$, and an increase in π^- production near $x = 0$. Similar arguments apply for the increase in π^- production near $x = 0$ for reaction (2) between 7 and 18.5 GeV/c and for the decrease in π^- production at $x > 0.5$ in reaction (3) between 8 and 18.5 GeV/c. Thus, while the total cross-section remains approximately constant, processes leading to 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 Figure 3 the structure function F(o) (averaged over $-.02 < x < +.02$) as a function of $s^{-\frac{1}{4}}$, as suggested by Abarbanel.[4] The data suggest that the distributions from the three reactions may indeed converge to the same value at very large energies although it seems clear that we are far from scaling in this kinematic region at present accelerator 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 distribution $G(p_{//}) = \int \frac{E}{\sigma_T} \frac{\partial^2\sigma}{\partial p_{//} \partial p_\perp^2} d p_\perp^2$ where all quantities are now evaluated in the laboratory.

We observe in Figure 4 that for the exotic reaction $\pi^+p \to \pi^-$ in the region $-0.1 < p_{//} < +0.2$ there is excellent agreement among the data at all three energies; for $p_{//} < -0.1$ GeV/c a small decrease with s; and for $p > +0.2$ GeV/c an increase with s. (This latter effect is the same as that already discussed in the c.m. system for x near zero). The inclusive analysis of Mueller[5] suggests that the distribution $G(p_{//})$ should approach the scaling limit as $A(p_{//}) + B(p_{//})s^{-\frac{1}{2}}$. Our $\pi^+p \to \pi^-$ distributions indicate that the function $B(p_{//})$ may have a zero in the region $-0.1 < p_{//} < 0.2$ GeV/c. In Figure 4 we also see that the distribution for $\pi^-p \to \pi^-$ for $p_{//} < 0.4$ GeV/c is falling rapidly with increasing s. This decrease is consistent with an approach to the cross-section for $\pi^+p \to \pi^-$ at higher energies as suggested by the factorization hypothesis,[5,6] i.e. the target proton fragments into π^- for both reactions in a similar way, independent of the incident charge. 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 GeV/c to $+0.4$ GeV/c. We have found that a large contribution to the π^+ in this region arises from the production and decay of $\Delta^{++}(1236)$, a process which has a smaller cross-section at 7.0 GeV/c than at 3.7 GeV/c.

To investigate the behavior of the laboratory distributions with energy we show in Figure 5 the integrals of the distributions for $p_{//} < 0$ as a function of $s^{-\frac{1}{2}}$ for each of our three reactions. We observe a rapid fall in the cross sections for the non-exotic reactions $\pi^+p \to \pi^+$ and $\pi^-p \to \pi^-$ as s increases. (Note that the $\pi^+p \to \pi^+$ distribution is plotted against the scale on the right). The exotic reaction $\pi^+p \to \pi^-$ has a very small energy dependence, suggestiong that although it has not yet reached the scaling limit, it may not be very far from it. The data also show that the cross-section for $\pi^-p \to \pi^-$ is indeed approaching that for $\pi^+p \to \pi^-$ at high energy.

To compare pion induced reactions with other reactions we show in figure 5 the data of Moffeit et al for $\gamma p \to \pi^-$ at 2.8, 4.7 and 9.3 GeV[7] and points for $K^+p \to \pi^-$ and $K^+p \to \pi^+$ at 12 GeV/c.[8] The $\gamma p \to \pi^-$ cross section is similar to the cross section for $\pi^-p \to \pi^-$ however it is smaller at comparable energies and falls more rapidly as s increases. The point for the exotic reaction $K^+p \to \pi^+$ at 12 GeV/c (plotted against the scale on the right) agrees better with the data for $\pi^+p \to \pi^+$ than with any other reaction. This is not surprising because in both these reactions there is a large contribution from the production and decay of Δ^{++}. The other exotic reaction $K^+p \to \pi^-$ yields a cross section comparable, but smaller, than that for $\pi^+p \to \pi^-$. It is amusing to speculate that the K^+ reaction, which has both $ab\bar{c}$ and ab exotic, may have already scaled at 12 GeV/c and that other reactions will tend towards this value (0.0037 ± 0.0002 GeV/c) at very high energies. The data for $\pi^+p \to \pi^-$ and $\pi^-p \to \pi^-$ are consistent with this speculation and if this "asymtotic" point is plotted at $s^{-\frac{1}{2}}$ equal zero it falls beautifully on a straight line through the $\pi^+p \to \pi^-$ data.

Finally, we consider the distribution $G(p_{//})$ evaluated in the projectile system. This is of interest because here we are looking at the fragmentation of the incident pion. Because two-prong events with short protons were not recorded during scanning we show only the data for $\pi^+p \to \pi^-$ in Figure 6. We observe that the data at 3.7 GeV/c and 7.0 GeV/c agree (perhaps fortuitously) in the region $0 < p_{//} < 0.8$ GeV/c; while the 18.5 GeV/c data are systematically lower in this region. (However, we should point out that some of the decrease may be a systematic experimental effect due to difficulties in reconstructing tracks of very high momenta.) The values of the distributions integrated over $p_{//} < 0.4$ GeV/c are given in the Table in Figure 6.

Comparison of our results with recent data of Beaupre et al.[9] who reported on reactions 1) and 2) at 8 and 16 GeV/c show similar trends in the F (x) distribution although our distributions at comparable energies are about 10 °/o higher. In the laboratory frame these authors report excellent agreement of the integrated distribution $\int_{-0.4}^{0} G(p_{//})dp_{//}$ for the exotic reaction $\pi^+ p \rightarrow \pi^-$ at 8 and 16 GeV/c. This observation is consistent with our data although the possibility of a small energy variation still exists.

In conclusion, the breadth of 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 $G(p_{//})$ for the slowly moving particles appears to be at or close to scaling for the exotic reaction (2) but far from it for the non-exotic reactions (1) and (3).

In the center of mass system for $x > 0.1$, we observe charge symmetry in F(x) for the non-exotic 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 x. This effect is due to the increase of higher multiplicity processes whose pions cluster close to $x = 0$ because of kinematic restrictions. Although we see negligible change with s in the non-exotic reactions, the fact that $\pi^+ \rightarrow \pi^+$ and $\pi^- \rightarrow \pi^-$ are not equal indicates that we are far from true scaling.

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Figure Captions

Figure 1 The inclusive distribution $F(x)$ in the center of mass (for definition see text). The errors shown are statistical only.

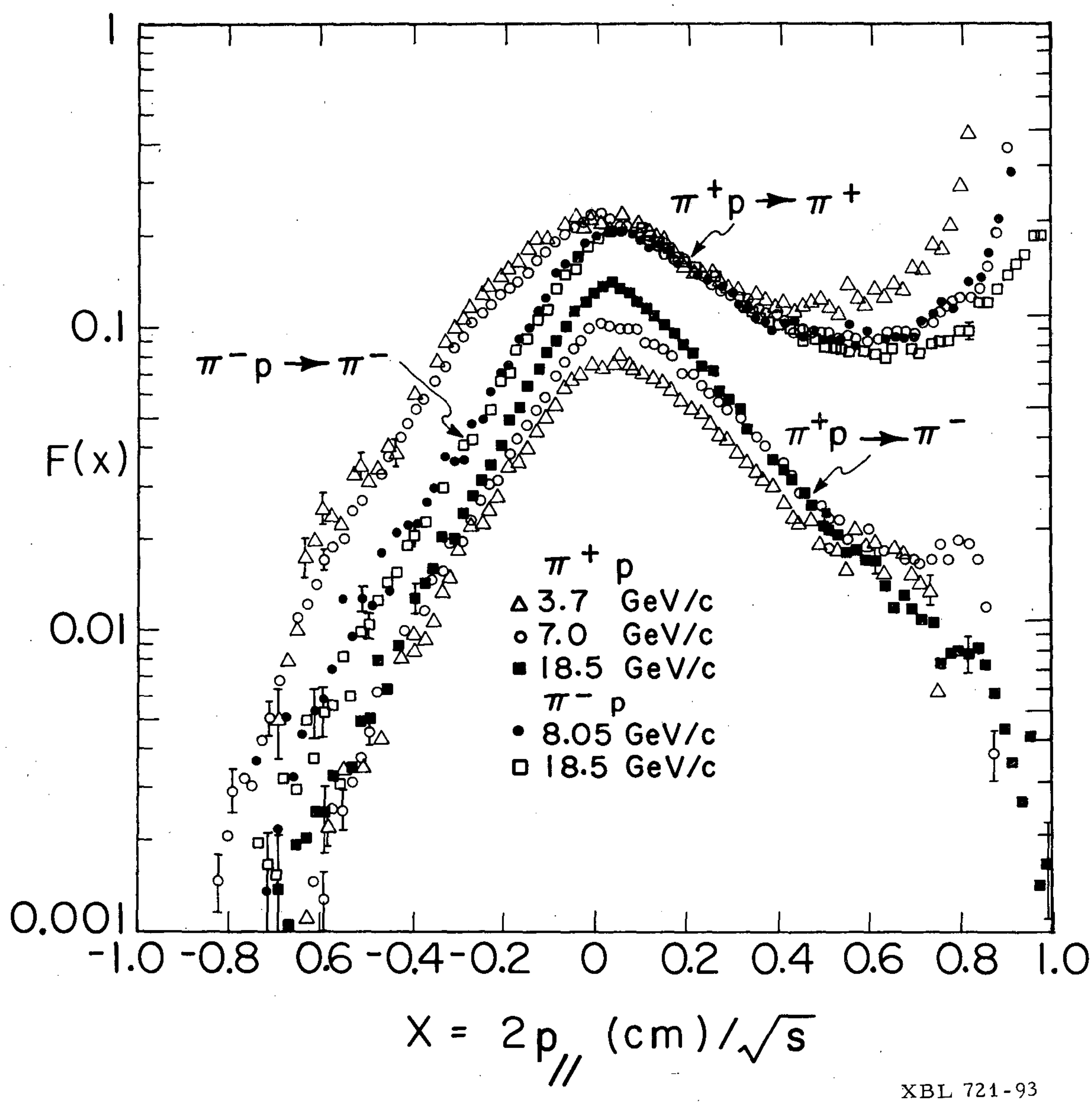
Figure 2 The distributions of $\sigma_T F(x)$ for events with different topologies for the reactions $\pi^+ p \to \pi^+$ (reaction 1) and $\pi^+ p \to \pi^-$ (reaction 2) at 3.7 and 7.0 GeV/c incident momenta.

Figure 3 $F(0)$ as a function of $S^{-\frac{1}{4}}$. Errors include systematics. The data point for $\pi^- p \to \pi^-$ at 24.5 GeV/c is from ref 2.

Figure 4 The inclusive distribution $G(p_{//})$ in the laboratory system (for definition see text). The errors shown are statistical only.

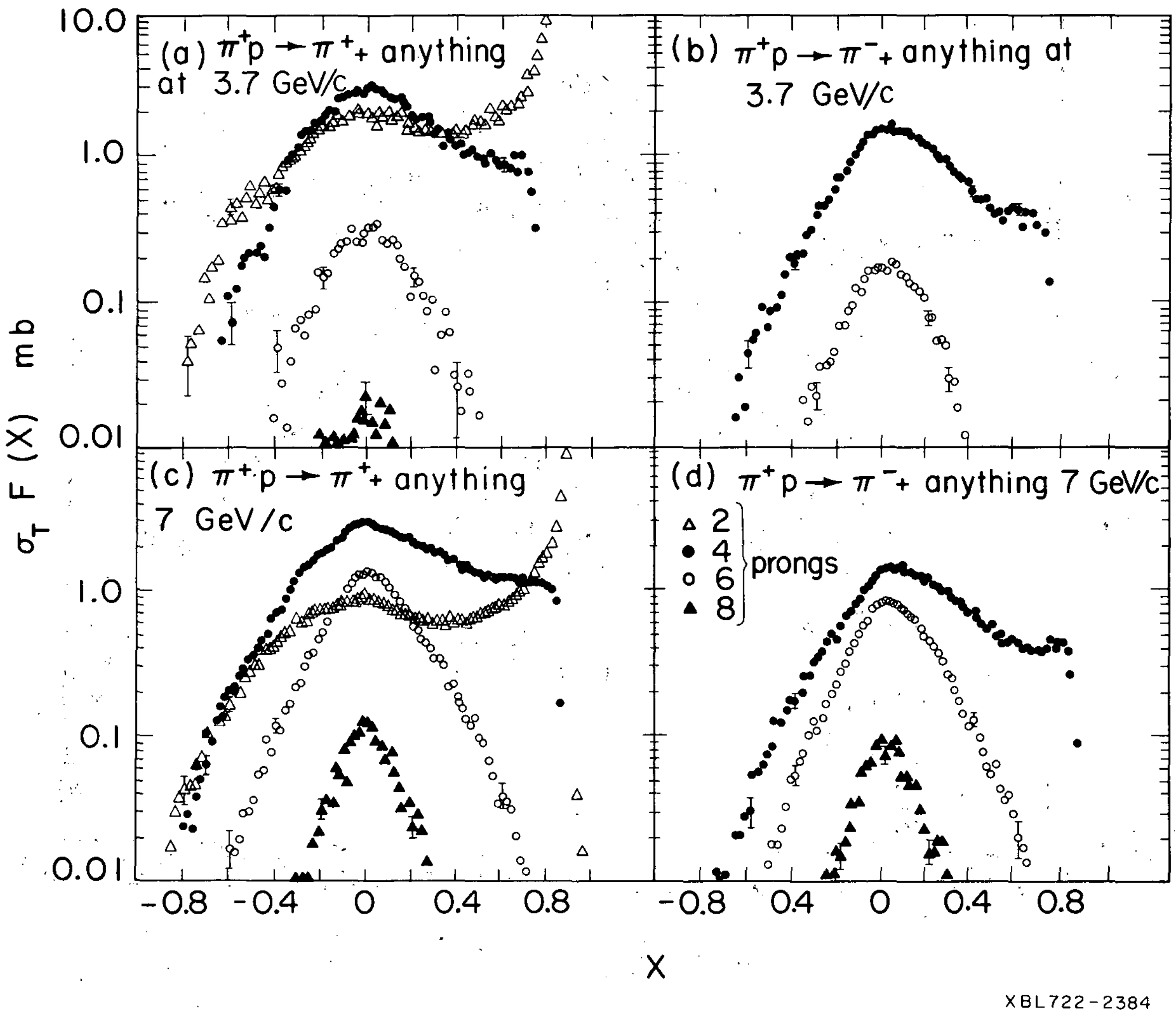
Figure 5 $\int_{-0.4}^{0} G(p_{//})dp_{//}$ as a function of $S^{-\frac{1}{2}}$. Errors include systematics. The point for $\pi^- p \to \pi^-$ at 24.5 GeV/c is from ref. 2, the data for γp are from ref. 7, and the points for $K^+ p$ from ref. 8.

Figure 6 The inclusive distribution $G\ (p_{//})$ 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.



1
0.1
0.01
0.001
F(x)
-1.0 -0.8 0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0
X = 2p// (cm)/√s
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
XBL 721-93

Fig. 1



(a) $\pi^+p \to \pi^+ +$ anything at 3.7 GeV/c
(b) $\pi^+p \to \pi^- +$ anything at 3.7 GeV/c
(c) $\pi^+p \to \pi^+ +$ anything 7 GeV/c
(d) $\pi^+p \to \pi^- +$ anything 7 GeV/c
2
4
6
8
prongs
10.0
1.0
0.1
0.01
σ_T F (X) mb
-0.8
-0.4
0
0.4
0.8
X
XBL722-2384

Fig. 2

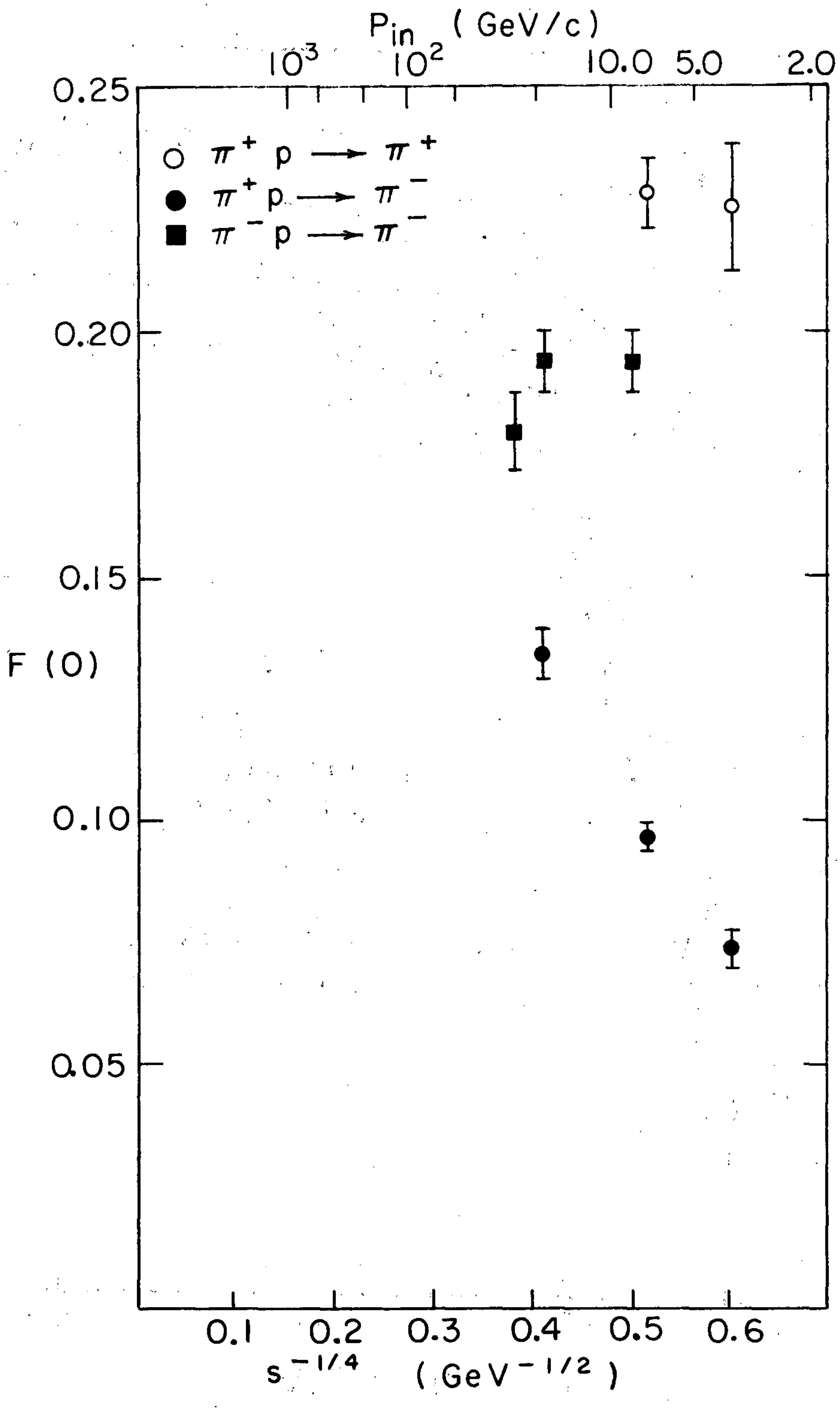
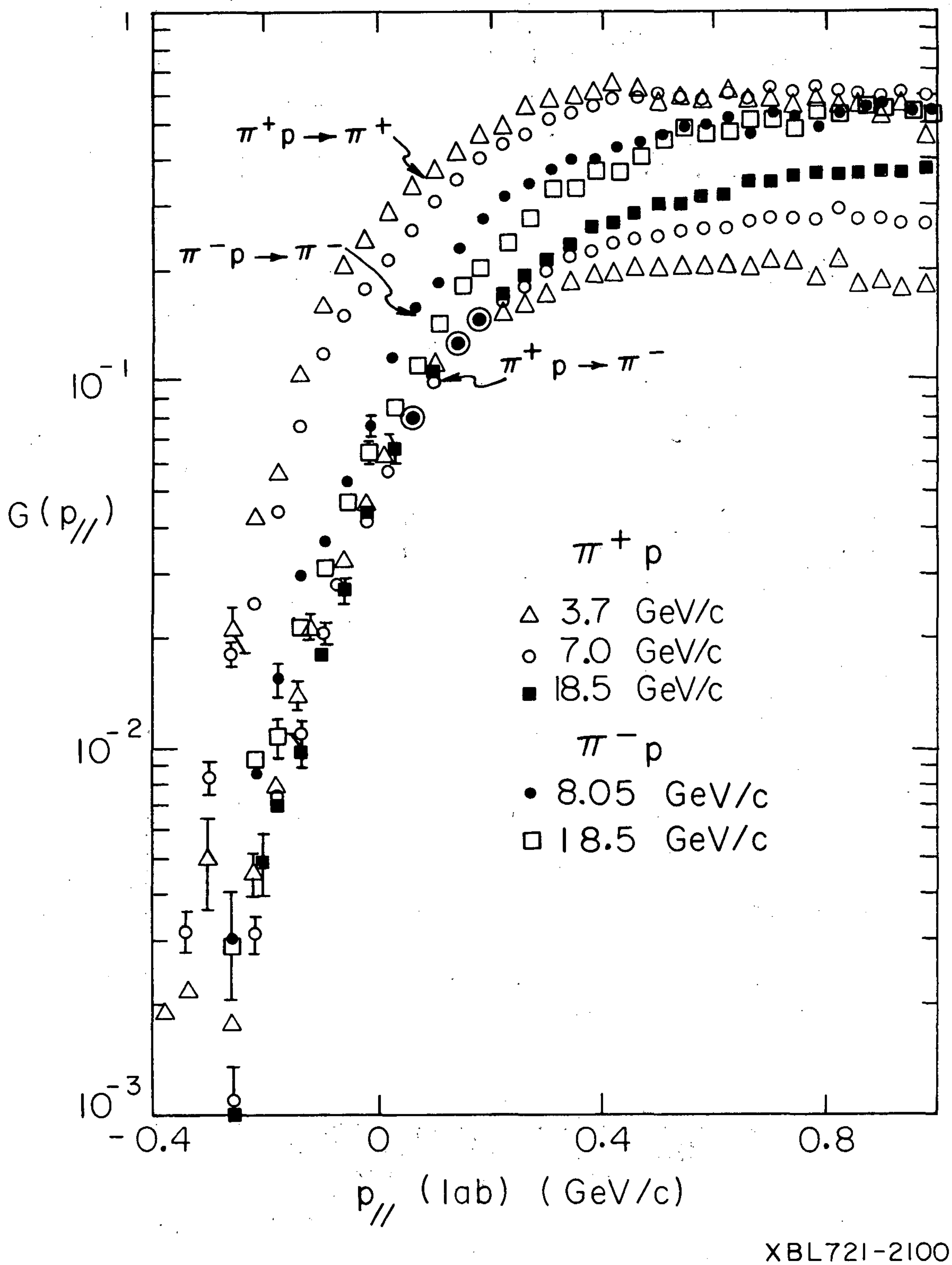
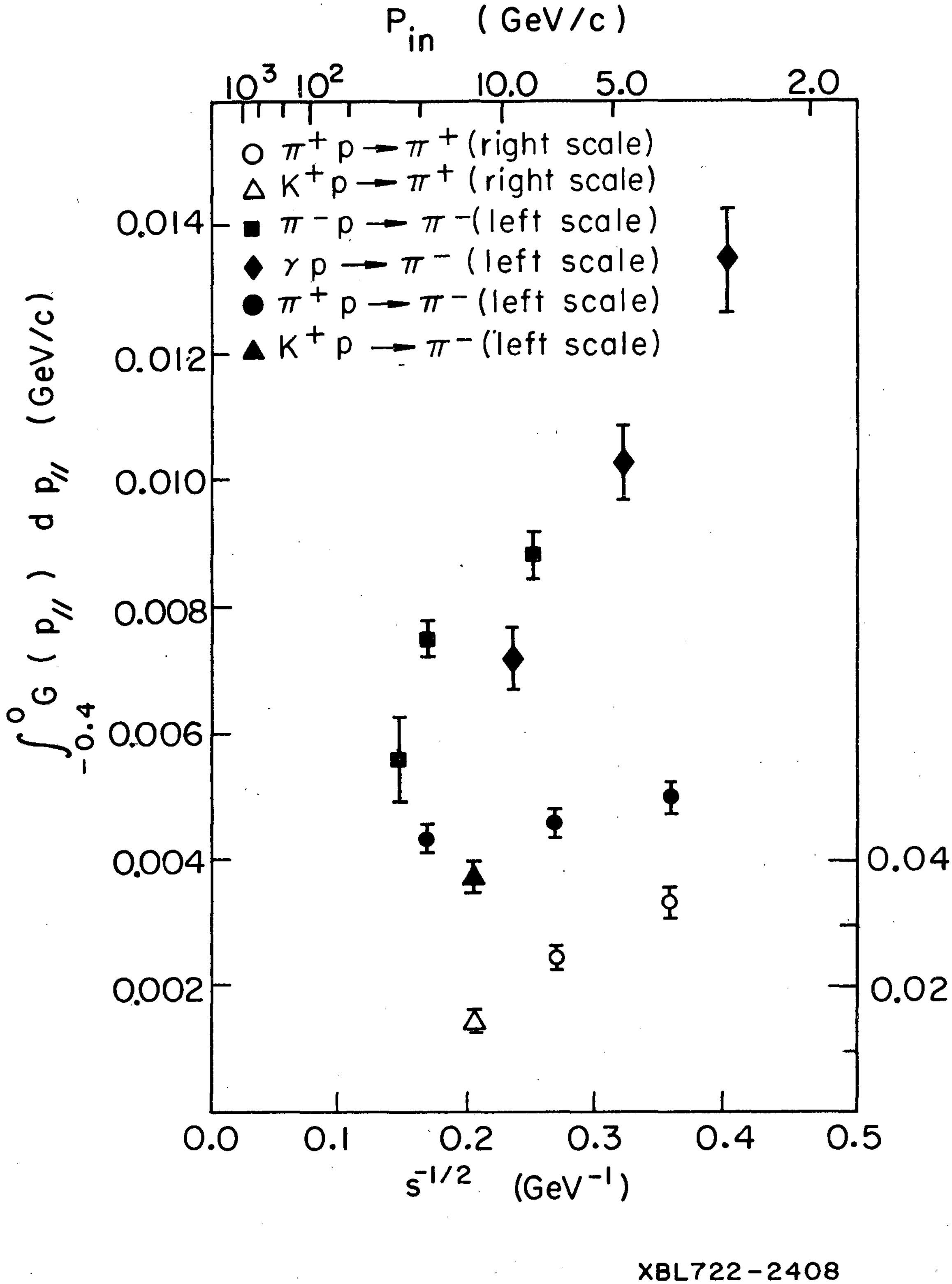

P_{in} (GeV/c)
10^3
10^2
10.0
5.0
2.0
0.25
0.20
0.15
0.10
0.05
F (0)
$\pi^+ p \longrightarrow \pi^+$
$\pi^+ p \longrightarrow \pi^-$
$\pi^- p \longrightarrow \pi^-$
0.1
0.2
0.3
0.4
0.5
0.6
$s^{-1/4}$ ($GeV^{-1/2}$)
XBL721-2157

Fig. 3



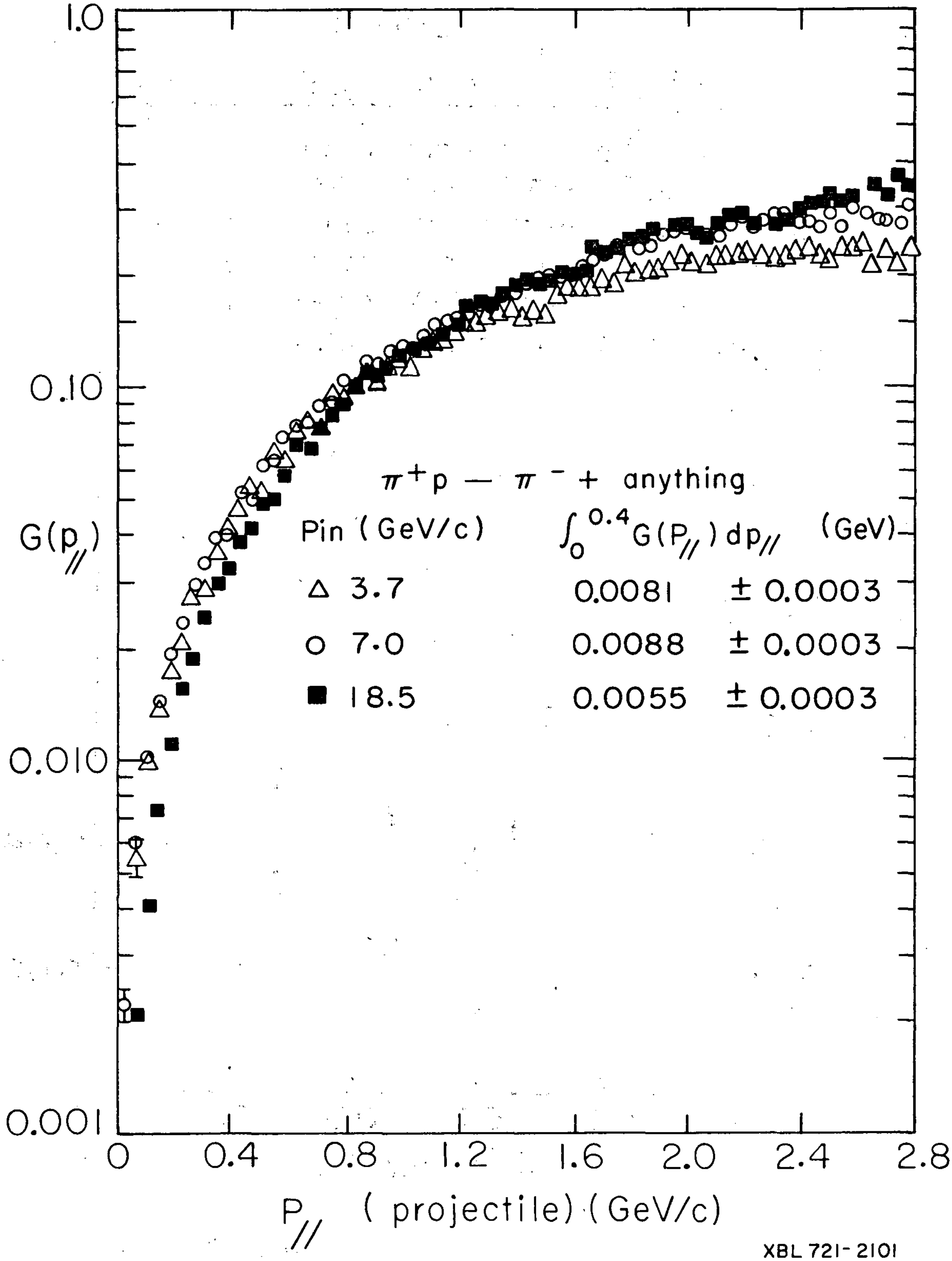
1
10^{-1}
10^{-2}
10^{-3}
-0.4
0
0.4
0.8
$G(p_{//})$
$p_{//}$ (lab) (GeV/c)
$\pi^+ p \to \pi^+$
$\pi^- p \to \pi^-$
$\pi^+ p \to \pi^-$
$\pi^+ p$
3.7 GeV/c
7.0 GeV/c
18.5 GeV/c
$\pi^- p$
8.05 GeV/c
18.5 GeV/c
XBL721-2100

Fig. 4



P in (GeV/c)
10³ 10² 10.0 5.0 2.0
○ π⁺ p → π⁺ (right scale)
△ K⁺ p → π⁺ (right scale)
■ π⁻ p → π⁻ (left scale)
◆ γ p → π⁻ (left scale)
● π⁺ p → π⁻ (left scale)
▲ K⁺ p → π⁻ (left scale)
∫_{-0.4}^{0} G (p//) d p// (GeV/c)
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.04
0.02
0.0 0.1 0.2 0.3 0.4 0.5
s^{-1/2} (GeV⁻¹)
XBL722-2408

Fig. 5



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
XBL 721-2101

Fig. 6

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