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The Approach to Scaling in Single-Particle Inclusive Hadron Scattering from 4 to 250 GeV/c

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ABSTRACT

Measurements of the dependence on $s = (p_a + p_b)^2$ of the cross section for single charged hadron production in the reactions $a + b \rightarrow c$ + anything are presented. Particle c is detected in a fixed interval of laboratory momentum and angle in the fragmentation region of the target proton. For the energy range studied there are significant departures from $A + Bs^{-\frac{1}{2}}$ energy dependence. When these departures are taken into account, asymptotic predictions such as Pomeron factorization can be tested.

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The approach to scaling in inclusive single particle hadron-hadron interactions in the target fragmentation region has been studied both theoretically and experimentally by many authors in the past few years.[1-4] In these analyses the Mueller-Regge phenomenology provides a framework for interpretation of the data.[5]

The Mueller theorem equates the invariant cross section for the process $a + b \rightarrow c$ + anything with a particular discontinuity of the forward amplitude for $a + b + \bar{c} \rightarrow a + b + \bar{c}$ scattering. In the limit where $u = (p_b - p_c)^2$, or y_L, the laboratory rapidity of c, is small and $s = (p_a + p_b)^2$ is large, the cross section is described by the sum of Regge exchanges between the incoming particle a and the $b\bar{c}$ system:

$$E \frac{d^3\sigma}{d^3p} = \gamma_a^P \beta_{b\bar{c}}^P (y_L, p_\perp)\, s^{\alpha_P(0)-1} + \sum_R \gamma_a^R \beta_{b\bar{c}}^R (y_L, p_\perp)\, s^{\alpha_R(0)-1} \tag{1}$$

In this expression the leading effect is from Pomeron exchange with $\alpha_P(0)$ usually taken to be one, and the secondary effects are ascribed to the exchange of Regge poles with $\alpha_R(0) \simeq 0.5$. It is assumed that the residues factorize into two terms γ_a, which describes the coupling of the singularity to the incident particle a, and $\beta_{b\bar{c}}(y_L, p_T)$, which describes the coupling of the singularity to the $b\bar{c}$ system. Terms from lower lying singularities are ignored, the assumption being that at sufficiently large s their contribution is small, leading to the general expression

$$E \frac{d^3\sigma}{d^3p} = A + Bs^{-\frac{1}{2}} \tag{2}$$

Previous studies of proton fragmentation have utilized bubble chamber data, and have confirmed, in general, the Mueller-Regge phenomenology. These studies, however, often integrate over substantial regions of y_L, $p_\perp$ phase space and often have limited statistical and systematic accuracy. In this paper we present results from a systematic study of the dependence of the invariant cross section on s, at fixed y_L and $p_\perp$ using an electronic detector. Specifically, we are concerned here with extrapolating cross sections to $s^{-\frac{1}{2}} = 0$ to test the factorization of the leading Pomeron singularity.

The data presented here were taken over a small, fixed region of phase space[6] corresponding approximately to $p_\perp = .3$ GeV/c and $y_L = .6, .4$, and .2 for produced π, K, and p, respectively. The range of incident momenta is 4 GeV/c $\leq p_a^{LAB} \leq$ 250 GeV/c, thereby allowing a good determination of the s-dependence of the invariant cross section at a particular fixed y_L and $p_\perp$. Data from 4 to 24 GeV/c were taken at the Brookhaven National Laboratory Alternating Gradient Synchrotron and the data at 150 and 250 GeV/c were taken at Fermilab.

For the Fermilab data, two differential Cerenkov counters and one threshold Cerenkov counter provided beam particle identification with negligible contamination of the various particle types. Electron contamination was eliminated by the insertion of 0.8 radiation lengths of lead at the first focus of the beam. Muon contamination is negligible for the high energy data presented here. The r-f bunching of the beam at Fermilab requires that r-f buckets populated by more than one particle be rejected. This was achieved by rejecting buckets in which three beam defining scintillation counters had pulse heights greater than 1.5 times the minimum ionizing pulse height. Studies of the intensity dependence of the cross section show no intensity dependence at a level of one per cent sensitivity. Similar studies of the dependence of the cross section on the horizontal and vertical steering of the beam show that the cross section is independent of mis-steering the beam by ± 0.5 cm in either direction at the level of three per cent sensitivity.

The instrumentation of the beam at Brookhaven is fully documented in Reference 7, and will not be discussed here. The same spectrometer was used at both laboratories. The spectrometer is described in detail in Reference 7, and only a brief summary of its operation is presented here.

The spectrometer is shown schematically in Figure 1. It is comprised of a small c-magnet, eighteen planes of multiwire proportional chambers, three scintillation counters, T1-T3, which are used for triggering and for particle identification, and a threshold Cerenkov counter C1. Produced protons are separated from faster particles by measuring the time of flight from the target to counter T2. The Cerenkov counter C1 is used to measure the ratio of pions to kaons in the remaining sample of fast particles.

The azimuthal acceptance of the spectrometer, $\Delta\Phi(\theta,p,z)$, is a function of the polar production angle θ, the momentum p, and the longitudinal position z of the produced particle. The acceptance is determined by tracing rays from the production vertex to the limit of the defining fiducial area at T2. The acceptance function integrated over z is then used to weight each event within the fiducial volume of the spectrometer. This acceptance correction, as well as energy loss and multiple scattering corrections, is tested by measuring elastic cross sections at low energy where the elastic peak in the missing mass squared distribution is easily resolved. A full discussion of the elastic calibration of the absolute normalization is also given in Reference 7

A further test of the normalization was made by integrating a local fit to the 12 GeV/c pp → $\pi^{\pm}$ data of Reference 8 over the acceptance of our spectrometer. The results agree with our measurements within one standard deviation (about two per cent).

The measured cross sections, integrated over the kinematic region specified in footnote 6, and with empty target backgrounds of typically three per cent subtracted, are displayed as a function of $s^{-\frac{1}{2}}$ in Figures 2a-d for produced π^-, π^+, K^+, and p, respectively. The production of K^- and $\bar{p}$ in this kinematic range is approximately at the limit of sensitivity of the experiment, and no further conclusions can be made concerning those cross sections.

The pion production cross sections, Figures 2a and 2b, are clearly not described well by the parameterization $A + Bs^{-\frac{1}{2}}$ over the large range of s shown. The solid line in these figures is a fit to the expression $A + Bs^{-\frac{1}{2}} + Cs^{-1}$ for $\pi^{\pm}$ and p, $\bar{p}$ production of pions, and a fit to $A + Bs^{-\frac{1}{2}}$ for the statistically less significent $K^{\pm}$ production of pions. The fit is constrained only by the requirement that particle and anti-particle production of a given particle be equal at $s^{-\frac{1}{2}} = 0$.

The production of K^+, Figure 2c is statistically less significant than $\pi^{\pm}$ production, and has been fit to $A + Bs^{-\frac{1}{2}}$. Note that for pp → K^+ as well as pp → $\pi^{\pm}$, the cross section rises to its asymptotic limit at these particular values of y_L, and p_T, as compared with pion production at negative y_L, where the cross sections appear to rise slowly and then fall to their asymptotic limits.[4]

Extrapolation of the above fits to $s^{-\frac{1}{2}} = 0$ permits asymptotic tests of Pomeron factorization which are independent of assumptions about the low energy behavior of the cross sections. Referring to equation (1), the ratio of the invariant cross sections for production of particle c by different particles a and a' is asymptotically equal to the total cross section ratio:

$$\frac{E\frac{d^3\sigma}{d^3p}(ap \rightarrow c)}{E\frac{d^3\sigma}{d^3p}(a'p \rightarrow c)} \underset{s^{-\frac{1}{2}}\rightarrow 0}{=} \frac{\gamma_a^P}{\gamma_{a'}^P} \underset{s^{-\frac{1}{2}}\rightarrow 0}{=} \frac{\sigma_{TOT}(ap)}{\sigma_{TOT}(a'p)} \qquad (3)$$

The ratio of the total cross sections in this limit is not uniquely defined since the experimentally measured cross sections are not asymptotically constant as the simple Regge pole model used here predicts. To represent this ambiguity we compare the ratio of the inelastic cross sections at $s^{-\frac{1}{2}} = 0$ with two total cross section ratios. The first is obtained from the parameterization of the diffractive part of the total cross section in Reference 9,

$$D_{ap} = C_{ap} \log \left(\frac{p_a^{LAB} + m_a}{b_a} \right)$$

evaluated at $p_a^{LAB} = 250$ GeV/c. The second cross section ratio is that obtained from the naive quark model:[10]

$$\sigma(\pi p) = \sigma(Kp) = \frac{2}{3} \sigma(pp).$$

The resulting tests of Pomeron factorization are presented in Table I. The data allow seven independent tests of Pomeron factorization. Except for K^+ production, where the statistics are bad, the results fall well within the range of the predictions. These results are in agreement with, and extend the result of Reference 2, which compares two cross sections which were assumed to be independent of s and were integrated from the kinematic limit to $y_{cm} = -.6$.

Further tests of the Mueller-Regge phenomenology, namely relations among the B terms in the above fits, are not possible with the limited high energy data available at present. We conclude that in single particle inclusive reactions there are significant departures from $A + Bs^{-\frac{1}{2}}$ below $P_a^{LAB} \approx 12$ GeV/c at the present y_L and $P_\perp$, and when these departures are taken into account, extrapolation to $s^{-\frac{1}{2}} = 0$ yields cross sections which satisfy Pomeron factorization well.

FIGURE CAPTIONS

Figure 1. Plan view of the spectrometer.

Figure 2. Cross sections integrated over the kinematic region in footnote 6, for the production of a) π^-, b) π^+, c) K^+, and d) p. The solid lines are fits to $A+Bs^{-\frac{1}{2}}$ or $A+Bs^{-\frac{1}{2}} + Cs^{-1}$ as described in the text.

REFERENCES AND FOOTNOTES

1. Representative reviews are: H. Boggild and T. Ferbel, Ann. Rev. Nucl. Sci. 24, 451(1974); R. G. Roberts in *Phenomenology of Particles at High Energies*, ed. R. L. Crawford and R. Jennings (Academic Press, London and New York, 1974); and T. Ferbel, *Proceedings of Summer Institute on Particle Physics*, SLAC Report No. 179, (1974).
2. J. Erwin, *et al*, Phys. Rev. Lett. 33, 1352 (1974).
3. P. A. Baker, *et al*, Nucl. Phys. B89, 189 (1975).
4. R. Schindler, *et al*, Phys. Rev. Lett. 33, 862 (1974); J. Whitmore, *et al*, Phys. Lett. 60B, 211 (1976).
5. A. H. Mueller, Phys. Rev. D2, 2963 (1970).
6. The boundaries of the acceptance are $.3\ \text{GeV/c} \le p_c^{\text{Lab}} \le .6\ \text{GeV/c}$ and $60.75° \le \theta_c^{\text{Lab}} + \frac{3.3°}{p_c^{\text{Lab}}} \le 64.25°$.
7. E. W. Beier, *et al*, to be published.
8. V. Blobel, *et al*, Nucl. Phys. B69 454 (1974).
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10. J.J.J. Kokkedee, *The Quark Model* (Benjamin, New York, 1969), and references therein. See also Reference 9.

TABLE I. Tests of Pomeron Factorization.

Cross section ratio	Asymptotic ratio for Produced Particle Type c				Predicted ratio	
	$c = \pi^-$	$c = \pi^+$	$c = K^+$	$c = p$	Ref. 9	Ref. 10
$\frac{\pi p \to c}{pp \to c}$	0.63 ± 0.03	0.62 ± 0.03	0.25 ± 0.18	0.62 ± 0.03	0.61 ± 0.02	0.67
$\frac{Kp \to c}{pp \to c}$	0.60 ± 0.06	0.45 ± 0.04		0.61 ± 0.08	0.53 ± 0.02	0.67

FIGURE 1

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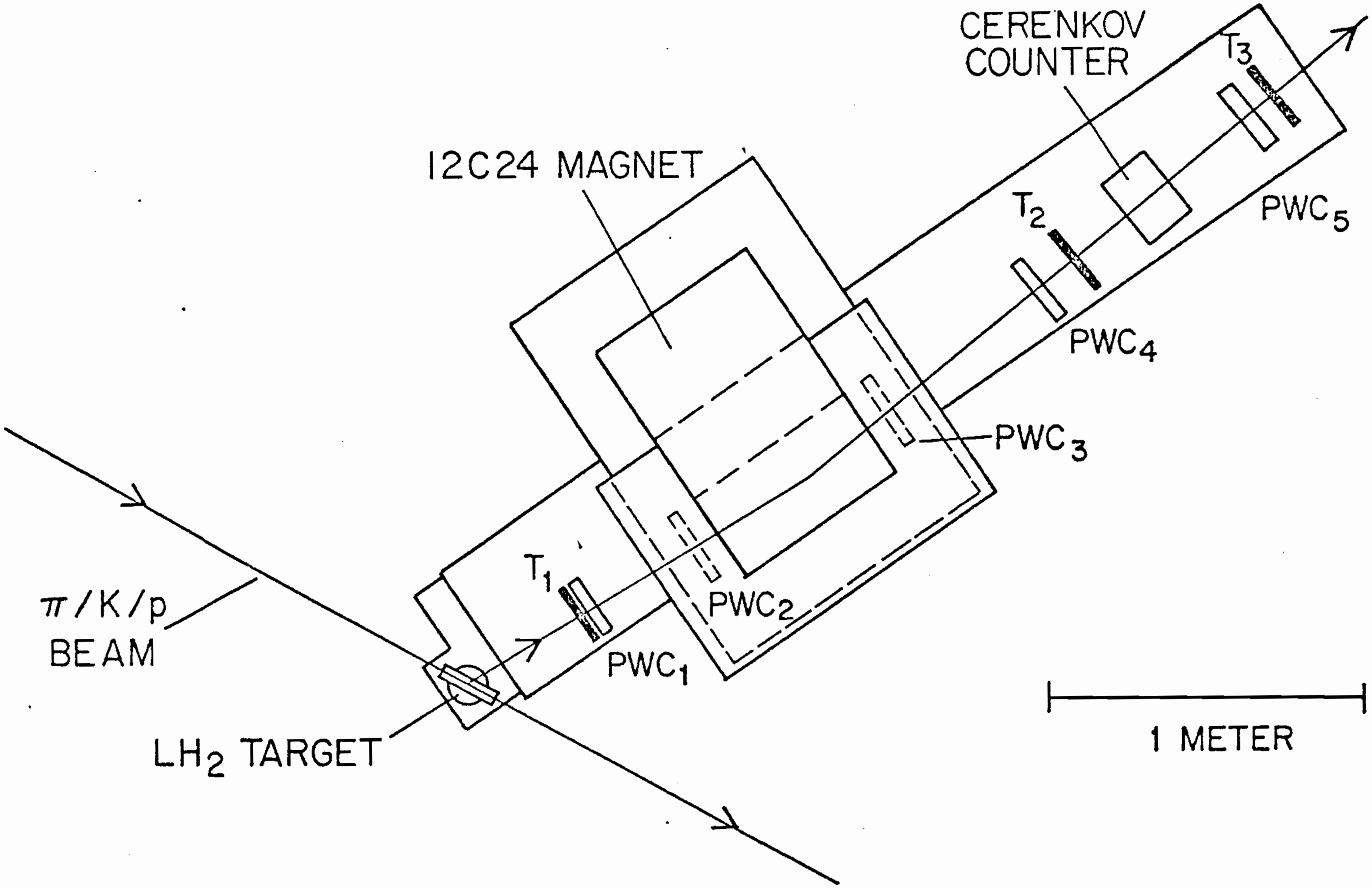
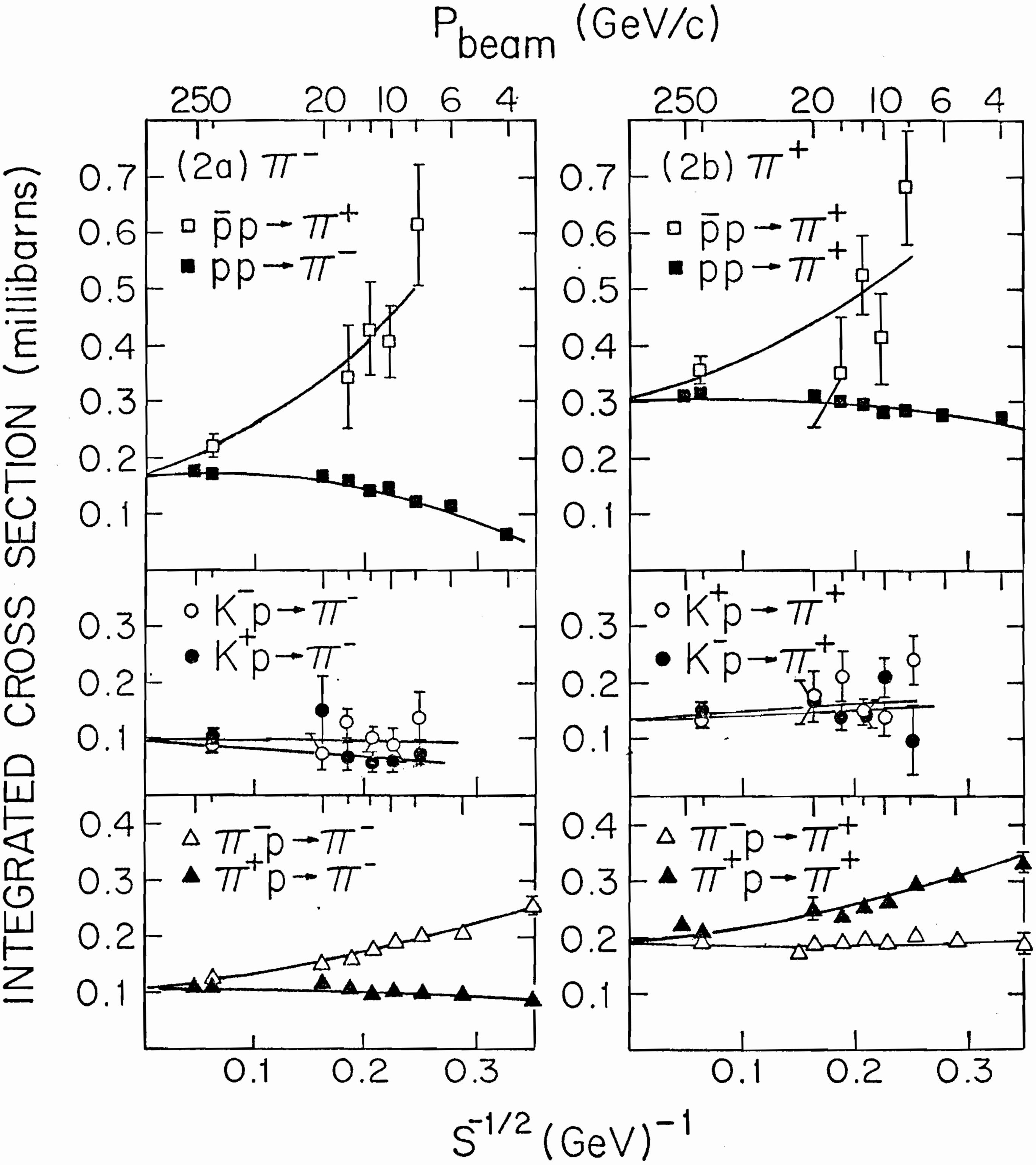
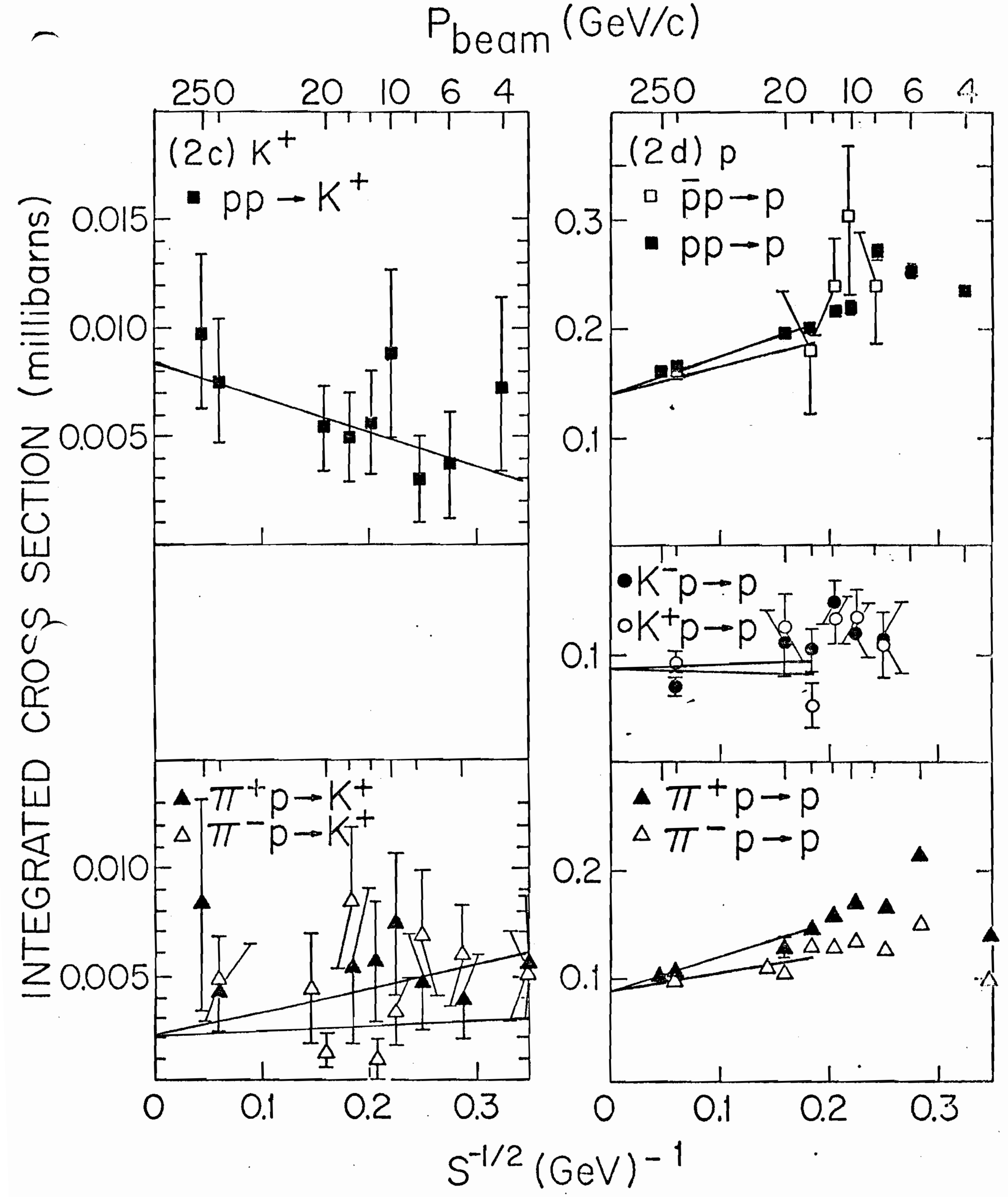
SINGLE PARTICLE SPECTROMETER





P_{beam} (GeV/c)
250
20
10
6
4
250
20
10
6
4
(2a) π^-
□ $\bar{p}p \rightarrow \pi^+$
■ $pp \rightarrow \pi^-$
(2b) π^+
□ $\bar{p}p \rightarrow \pi^+$
■ $pp \rightarrow \pi^+$
○ $K^-p \rightarrow \pi^-$
● $K^+p \rightarrow \pi^-$
○ $K^+p \rightarrow \pi^+$
● $K^-p \rightarrow \pi^+$
△ $\pi^-p \rightarrow \pi^-$
▲ $\pi^+p \rightarrow \pi^-$
△ $\pi^-p \rightarrow \pi^+$
▲ $\pi^+p \rightarrow \pi^+$
INTEGRATED CROSS SECTION (millibarns)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.3
0.2
0.1
0.4
0.3
0.2
0.1
0.1
0.2
0.3
$S^{-1/2}$ (GeV)$^{-1}$



P_beam (GeV/c)
250
20
10
6
4
(2c) K+
pp → K+
0.015
0.010
0.005
π+p → K+
π−p → K+
0.010
0.005
INTEGRATED CROSS SECTION (millibarns)
(2d) p
p̄p → p
pp → p
0.3
0.2
0.1
K−p → p
K+p → p
0.1
π+p → p
π−p → p
0.2
0.1
0
0.1
0.2
0.3
S^-1/2 (GeV)^-1