national accelerator laboratory

NAL-Pub-74/45-EXP
7200.037

(Submitted to Phys. Rev. Letters)

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June 1974

Operated by Universities Research Association Inc. Under Contract with the United States Atomic Energy Commission

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ABSTRACT

Single-particle distributions in transverse and longitudinal momentum have been studied in pp interactions at 300 GeV/c. By comparing these distributions for different multiplicities of produced particle and with published low-energy data we put forth the hypothesis of a new type of scaling: the shape of distributions in p_T and p_L are independent of multiplicity and incident energy.

The scaling behavior of a distribution, $f(x_1, x_2)$ with independent variables x_1 and x_2, can be defined in terms of a homogeneous equation,

$$f(\lambda_1 x_1, \lambda_2 x_2) = \lambda\, f(x_1, x_2)\,. \tag{1}$$

The distribution f scales if there exist scaling parameters λ_1, λ_2, and λ for which Eq. (1) is satisfied. For the special choice: $\lambda_1 = 1/\langle x_1 \rangle$, $\lambda_2 = 1/\langle x_2 \rangle$, and $\lambda = \langle x_1 \rangle \langle x_2 \rangle$, we obtain the scaling equation

$$f(x_1, x_2) = \frac{1}{\langle x_1 \rangle \langle x_2 \rangle}\; f\left(\frac{x_1}{\langle x_1 \rangle}, \frac{x_2}{\langle x_2 \rangle}\right)\,. \tag{2}$$

We propose a new hypothesis of scaling for high-energy collisions: distributions resulting in multiparticle production at high energies satisfy Eq. (2) when $x_1 = p_T$ and $x_2 = p_L$. In other words, the distributions maintain their shapes if they are plotted against the <u>mean</u> variable $x_i/\langle x_i \rangle$ and properly normalized. The energy, initial state, and multiplicity dependencies lie in the average value $\langle x_i \rangle$. It can be shown that Eq. (2) maintains its form when it is integrated over either one of the variables.

In this Letter we present an analysis of the inclusive single-particle distributions in the transverse (p_T) and the longitudinal (p_L) momentum variables in the center-of-mass system. These events were produced by 300 GeV/c protons in the 30-in. hydrogen bubble chamber at the Fermi National Accelerator Laboratory. A sample of 877 events (see Table I) with prong multiplicity as high as 26 prongs were track matched in three views by physicists and scanners on the high magnification (X72) FermiLab-designed "MOMM" tables using the bubble pattern of the charged track.

These events were then measured and processed through the program TVGP. In this study we restricted ourselves to the negatively charged secondary tracks, to which we have assigned the pion mass. Based on our previous determination of the K_S^o inclusive cross section[1] at this energy, we estimate our kaon contamination as about 10% of the negatively charged tracks.

According to the hypothesis mentioned above, we should test the following scaling equation

$$\frac{1}{\sigma}\frac{d^2\sigma}{dp_T dp_L} = \frac{1}{<p_T><p_L>}\,\phi\left(\frac{p_T}{<p_T>}, \frac{p_L}{<p_L>}\right), \tag{3}$$

where ϕ is a function independent of incident energy, initial states, and prong multiplicity.

In Fig. 1 we examine the π^- spectra in transverse momentum from pp interactions at 13,[2] 21,[2] 28.5,[2] and 300 GeV/c by plotting $(d\sigma/dp_T)<p_T>/\sigma$ versus $p_T/<p_T>$. We observe that the data are remarkably similar and strongly hint at a universal function despite the fact that a wide range of incident momenta and prong multiplicities were selected.

In Fig. 2 we plot $(d\sigma/dp_L)<p_L>/\sigma$ versus $p_L/<p_L>$ and show again that the data are consistent with a universal function. We note that if these data are plotted in the Feynman variable x ($= 2p_L/\sqrt{s}$, where $\sqrt{s}$ is the c.m. energy) instead of the mean variable $p_L/<p_L>$, the distributions will not scale for such diverse prong multiplicities as we have presented in Fig. 2. The fact that the shapes of the distributions are similar leads us to speculate that: (a) there is one dominant production mechanism, perhaps thermodynamic in origin, in high-energy collisions, and (b) dependences in incident energy, initial state,[4] and prong multiplicity are manifested only in the average values.

To show that the data presented in Figs. 1 and 2 follow a universal distribution, we fitted the data to two functions suggested by the thermodynamic model[2, 3]

$$\phi_T = a\left(\frac{p_T}{<p_T>}\right)^c \exp\left[-b\left(\frac{p_T}{<p_T>}\right)\right] \tag{4}$$

$$\phi_L = k \exp\left[-p\left(\frac{p_L}{<p_L>}\right) - q\left(\frac{p_L}{<p_L>}\right)^2\right] \tag{5}$$

and obtained the following results: $a = 6.23 \pm 0.52$, $b = 2.37 \pm 0.04$, $c = 1.37 \pm 0.03$, $k = 0.91 \pm 0.15$, $p = 0.83 \pm 0.04$, and $q = 0.03 \pm 0.01$. The χ^2/degree of freedom are 104/109 and 134/100 respectively. If the average values are not divided out, the shapes of the distributions are different. To test this point, we fitted the same data without dividing them by the average value (namely the distributions: $d\sigma/dp_T\,(1/\sigma)$ versus p_T and $d\sigma/dp_L\,(1/\sigma)$ versus p_L) and using the same functional form given by Eqs. (4) and (5). The results were poor and we obtained χ^2 of 757 and 1509 respectively.

The correlation between p_T and p_L can be studied in terms of the ratios of moments $<p_T^m\, p_L^n>/<p_T>^m <p_L>^n$, which are constants according to Eq. (3). We examine the first moment of this correlation. From Eq. (3) one can derive:

$$<p_T(p_L)> \equiv \frac{\int_0^\infty p_T \frac{d^2\sigma}{dp_T\, dp_L}\, dp_T}{\int_0^\infty \frac{d^2\sigma}{dp_T\, dp_L}\, dp_T} = <p_T>\, g\left(\frac{p_L}{<p_L>}\right). \tag{6}$$

In Fig. 3 we plot 300 GeV/c data and data at 19 GeV/c.[5] The figure shows that within the present statistics Eq. (6) is satisfied. Thus the shape of the well-known "seagull effect" (p_T and p_L correlation) as given by $g(p_L/<p_L>)$ is also shown to be independent of energy and prong multiplicity.

Other variables can be used in Eq. (2). For example, if $x_1 = n_c$, the number of charged particles, and $x_2 = n_0$, the number of neutral particles, then we have the familiar Koba-Nielsen-Olesen scaling.[6] It may further be possible to generalize Eq. (2) to more than two variables.

In summary we note the following:

(i) The scaling hypothesis proposed in this Letter should be regarded as an attempt, without resorting to specific theoretical models, to summarize the bulk of the pion production data presently available from high-energy hadron collisions.

(ii) Insofar as these distributions are universal and independent of energy and initial state, we conclude that there is one dominant mechanism for pion production at high energies and the process can be described in terms of only a few number of parameters. One such candidate is the thermodynamic model in which a very important concept (parameter) is the temperature of the hadron system.

(iii) The scaling hypothesis makes no mention of the energy dependence of the average value in the distribution. Consequently, one can study this dependence on energy and initial state as a separate problem (for example, to see whether p_T increases logarithmically or as a power).

We are grateful to the FermiLab Film Analysis Facility staff for their careful and painstaking work in track matching and measuring the high multiplicity events.

REFERENCES

*Supported in part by the U. S. Atomic Energy Commission and the National Science Foundation.

[1]F. T. Dao et al., Phys. Rev. Letters 30, 1151 (1973).

[2]D. B. Smith, Ph.D. thesis, Lawrence Berkeley Laboratory Report UCRL-20632, 1971 (unpublished). See also D. B. Smith et al., Phys. Rev. Letters 23, 1064 (1969).

[3]R. Hagedorn, Nuovo Cimento 25, 1017 (1962).

[4]There are no published data on single-particle distributions from high energy (> 100 GeV/c) πp interactions. However we have studied the initial state dependence of the functions ϕ_T and ϕ_L given in Eqs. (4) and (5), using the 25 GeV/c $\pi^- p$ data of J. W. Elbert et al. [Phys. Rev. Letters 20, 124 (1968) and J. W. Elbert, Ph.D. thesis, University of Wisconsin (1971)]. We found that the π^+ (non-leading particle) spectra in this case have the same functional dependence as the π^- spectra from pp collisions.

[5]H. Bøggild et al., Nucl. Phys. B57, 77 (1973).

[6]Z. Koba, H. B. Nielsen, and P. Olesen, Nucl. Phys. B40, 317 (1973). For an experimental review of Koba-Nielsen-Olesen scaling, see P. Slattery, Phys. Rev. D7, 2073 (1973) and F. T. Dao and J. Whitmore, Phys. Letters 46B, 252 (1973) and references therein.

[7] A. Firestone et al., Fermi National Accelerator Laboratory Report NAL-Pub-74/39-EXP, CALT-68-438, and UCLA-1098 (1974).

Table I. Events From 300 GeV/c pp Interactions Used in This Analysis.

Prong Multiplicity n_c	Number of Events[a]	$\langle p_T \rangle$ in GeV/c	$\langle p_L \rangle$ in GeV/c
4	515	0.34±0.02	0.93±0.04
6	246	0.35±0.02	0.72±0.03
8	69	0.36±0.02	0.64±0.05
20	17	0.33±0.02	0.41±0.04
22	17	0.31±0.02	0.43±0.04
24	7	0.28±0.02	0.44±0.04
26	6	0.33±0.03	0.41±0.06

[a] To increase statistics, we have in our subsequent analysis combined these events into two groups: $4 \le n_c \le 8$ and $20 \le n_c$, and properly weighted them according to the topological cross sections (see Ref. 7).

FIGURE CAPTIONS

Fig. 1. Plot of $<p_T>/\sigma(d\sigma/dp_T)$ versus $p_T/<p_T>$ for the reactions $pp \to \pi^-$. Low-energy data at 13, 21, and 28.5 GeV/c are from Ref. 2.

Fig. 2. Plot of $<p_L>/\sigma(dp/dp_L)$ versus $p_L/<p_L>$. Low-energy data at 13, 21, and 28.5 GeV/c are from Ref. 2.

Fig. 3. Plot of $<p_T(p_L)> / <p_T>$ versus $p_L/<p_L>$, where $<p_T(p_L)> \equiv \int_0^\infty (d^2\sigma/dp_T dp_L) p_T dp_T / \int_0^\infty (d^2\sigma/dp_T dp_L) dp_T$. Data at 19 GeV/c are from Ref. 5.

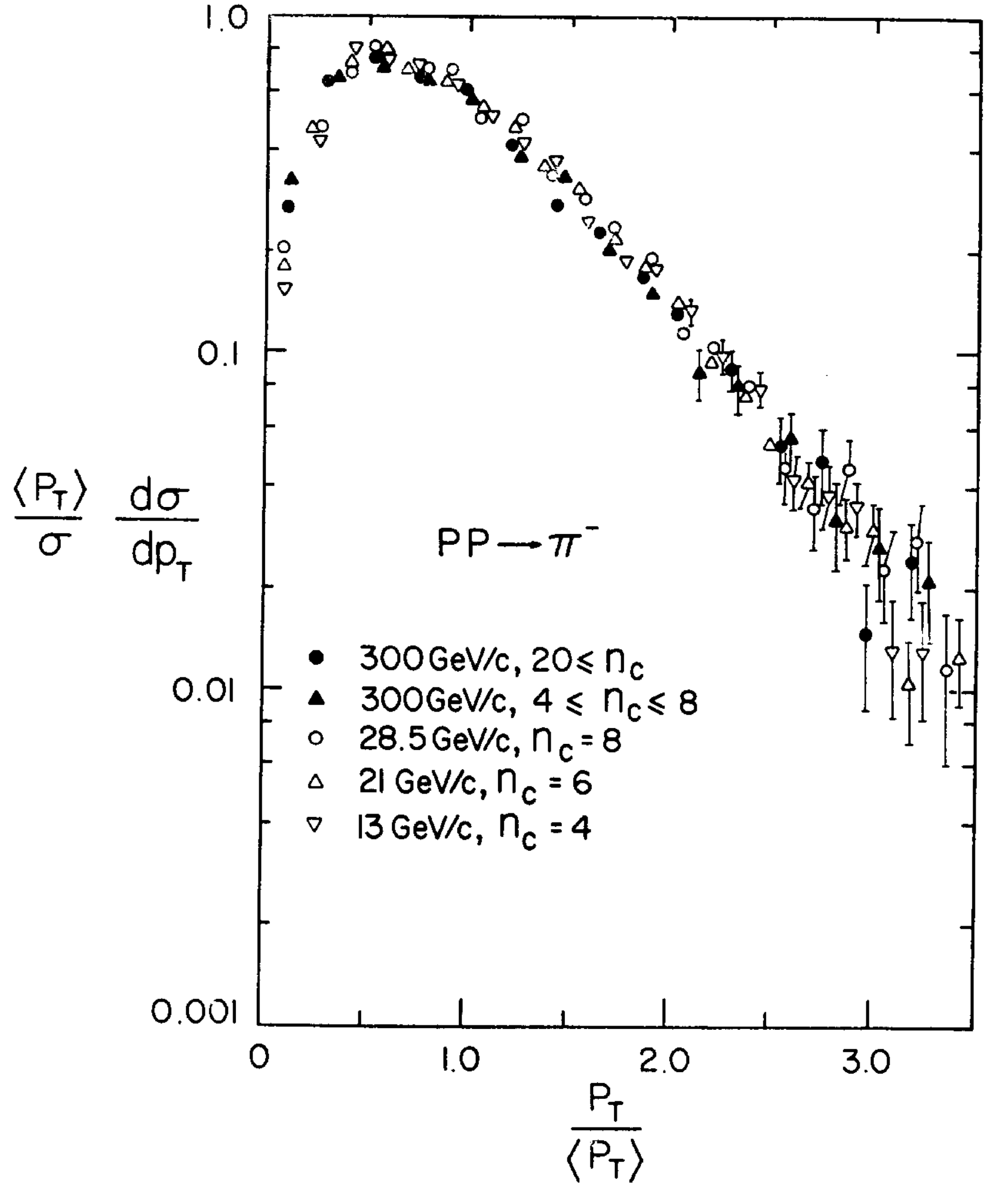
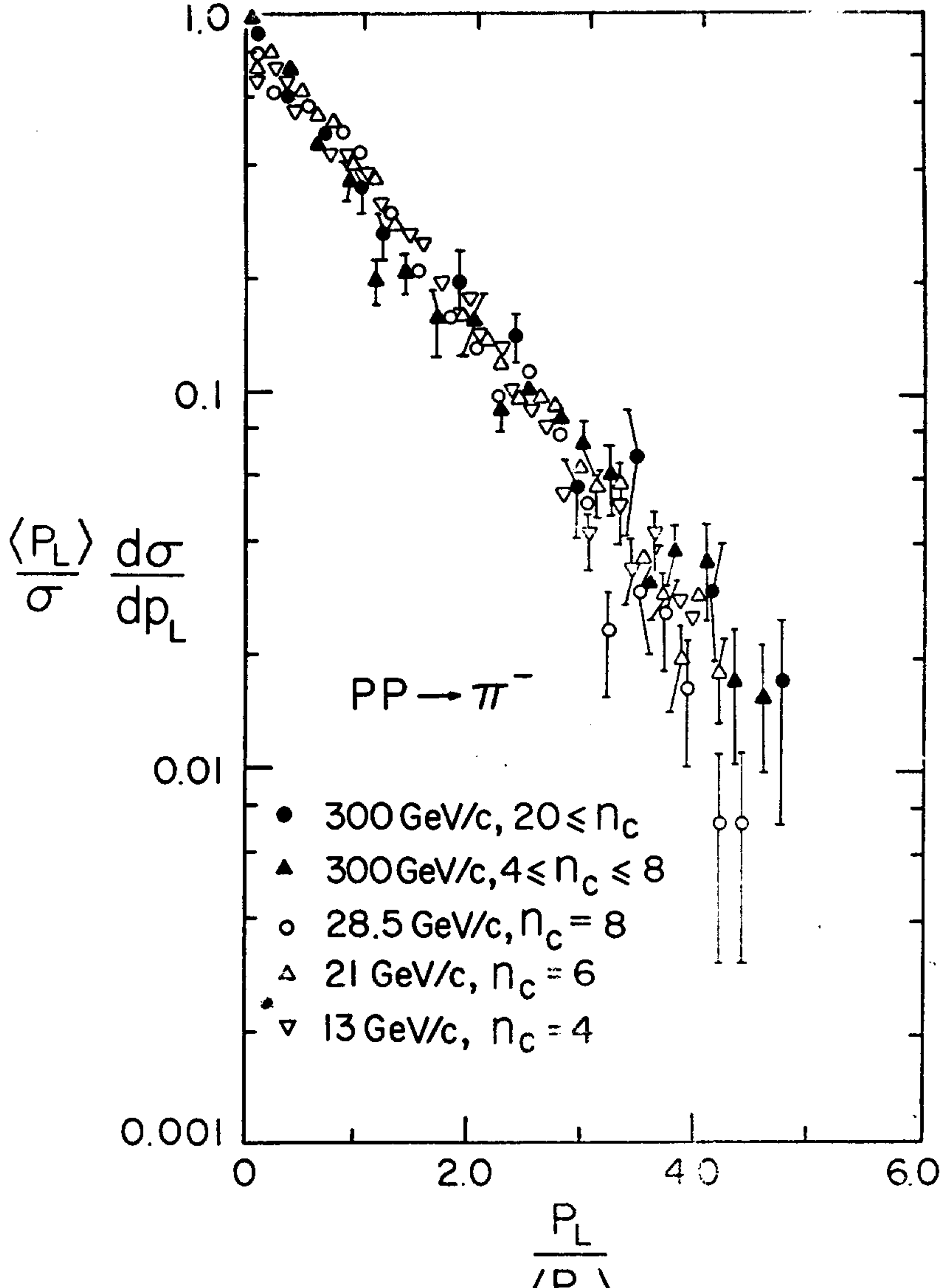
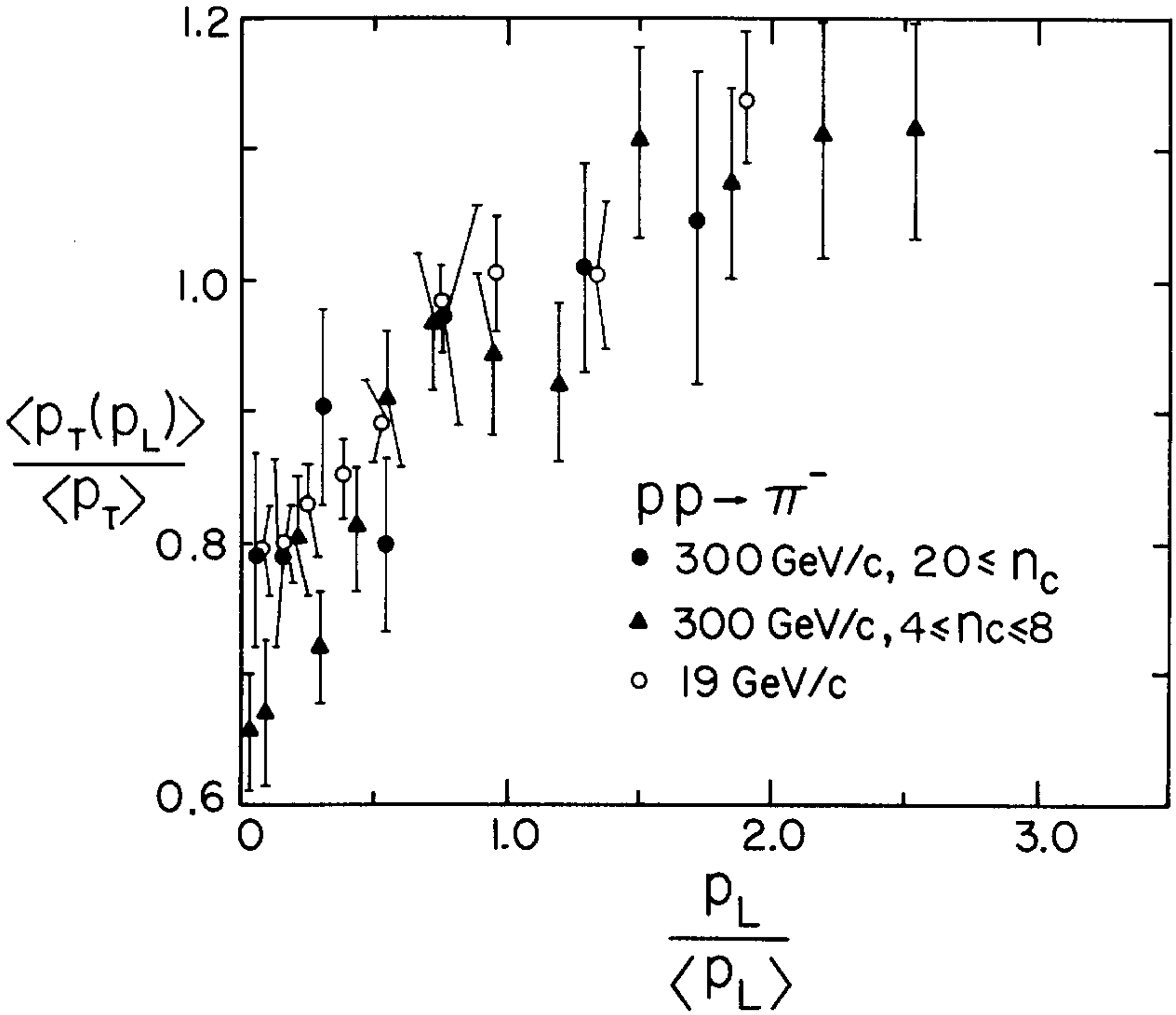

1.0
0.1
0.01
0.001
0
1.0
2.0
3.0
$\frac{\langle P_T \rangle}{\sigma} \frac{d\sigma}{dp_T}$
$PP \to \pi^-$
● 300 GeV/c, 20 ≤ n_c
▲ 300 GeV/c, 4 ≤ n_c ≤ 8
○ 28.5 GeV/c, n_c = 8
△ 21 GeV/c, n_c = 6
▽ 13 GeV/c, n_c = 4
$\frac{P_T}{\langle P_T \rangle}$

Fig. 1



1.0
0.1
0.01
0.001
$\frac{\langle P_L \rangle}{\sigma} \frac{d\sigma}{dp_L}$
$PP \rightarrow \pi^-$
300 GeV/c, 20 ≤ n_c
300 GeV/c, 4 ≤ n_c ≤ 8
28.5 GeV/c, n_c = 8
21 GeV/c, n_c = 6
13 GeV/c, n_c = 4
0
2.0
4.0
6.0
$\frac{P_L}{\langle P_L \rangle}$

Fig. 2



1.2
1.0
0.8
0.6
0
1.0
2.0
3.0
$\frac{\langle p_T(p_L) \rangle}{\langle p_T \rangle}$
$\frac{p_L}{\langle p_L \rangle}$
$pp \to \pi^-$
300 GeV/c, $20 \leq n_c$
300 GeV/c, $4 \leq n_c \leq 8$
19 GeV/c

Fig. 3