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ABSTRACT

Data on hadron-proton collisions ranging from 1 to 300 GeV/c in incident momentum show evidence for an energy-dependent approach to a single semi-inclusive scaling curve for the charged multiplicity cross sections as predicted by Koba, Nielsen, and Olesen. The onset of this scaling behavior is shown to depend on the initial state hadrons. The relation between the onset of this apparent scaling and the approach to a constant value of $\langle n \rangle / D$ is suggestive of a two-component process.

In recent publications,[1,2] it has been shown that, for proton-proton collisions between 50 and 300 GeV/c incident beam momentum, the topological cross sections are consistent with an asymptotic semi-inclusive scaling prediction of Koba, Nielsen, and Olesen (KNO).[3] In this Letter, evidence is presented to show that this semi-inclusive scaling property is more general and appears to be satisfied in several other types of hadron-proton collisions.[4] The energy at which this scaling is achieved depends upon the type of beam hadron and, in general, is equal to or lower than 50 GeV/c. In this regard, the $\bar{p}p$ system is shown to have quite distinctive features. The results of this study suggest that KNO scaling is achieved as a result of the combination of leading particle and multiperipheral processes.

The KNO prediction[3] for the asymptotic semi-inclusive scaling of the topological cross sections has the form

$$\langle n \rangle \frac{\sigma_n(s)}{\sigma_{inel}(s)} \xrightarrow[s \to \infty]{} \psi\left(\frac{n}{\langle n \rangle}\right), \tag{1}$$

where $\sigma_n(s)$ is the cross section for producing n charged particles at c.m. energy $\sqrt{s}$, σ_{inel} is the total inelastic cross section, $\langle n \rangle$ is the average charged particle multiplicity and $\psi(n/\langle n \rangle)$ is an energy-independent function. Furthermore, such a scaling law (1) leads directly[3] to the requirement that $\langle n \rangle / D$ be a constant, where D is the dispersion of the multiplicity distribution: $D^2 = \langle n^2 \rangle - \langle n \rangle^2$.

A study[1] of pp collision topological cross sections has indicated that data at 50, 69, 102, 205, and 303 GeV/c lie on a single energy-independent curve when $\langle n \rangle \sigma_n/\sigma_{inel}$ is plotted versus $n/\langle n \rangle$. The observation was made, however, that lower energy pp data show significant departures from this curve.

Figure 1 presents a compilation[5] of the values of $\langle n \rangle / D$ for A+ proton collisions (where A may be p, $\bar{p}$, $\pi^{\pm}$, $K^{\pm}$, γ) at laboratory momenta ranging from 1 to 300 GeV/c.[6] For momenta greater than ~50 GeV/c, the data appear consistent with a constant value of $\langle n \rangle / D \simeq 2$. It should also be noted that the energy dependence of the approach to this value varies with the type of particle A. In particular, it appears that $\bar{p}p$ interactions give rise to a multiplicity distribution which is consistent with $\langle n \rangle / D = 2$ for beam momenta as low as ~7 GeV/c.

A notable feature of Fig. 1 is the difference between the $\bar{p}p$ and the other A + p interactions. While the latter all approach $\langle n\rangle/D \simeq 2$ from above, the $\bar{p}p$ data approach this value from below. This trend in $\bar{p}p$ collisions is related to the statistical nature of particle production in the annihilation process which dominates the cross sections at energies below 5 GeV/c. For example, a Poisson gas model would predict an increasing value for $\langle n\rangle/D \sim \langle n\rangle^{\frac{1}{2}} \sim (\ln s)^{\frac{1}{2}}$. Contrary to this, the decreasing value of $\langle n\rangle/D$ observed in the other hadronic collisions at low energies may result from a diffractive-type process which would predict[7] $\langle n\rangle/D \sim s^{-\frac{1}{4}} \ln s$.

In Fig. 2(a) the KNO scaling prediction is examined for all data that are consistent with $\langle n\rangle/D \simeq 2$ by plotting $\langle n\rangle\, \sigma_n/\sigma_{inel}$ as a function of $z = n/\langle n\rangle$. The pp data are shown as the dashed curve which represents Slattery's fit[1] to the 50-300 GeV/c data. The $\pi^- p$ and $\bar{p}p$ data are in remarkably good agreement with the pp curve considering (a) the wide range of energies shown in the figure ($\bar{p}p$ from 6.9 to 15 GeV/c and $\pi^- p$, pp from 50 to 303 GeV/c), and (b) the fact that the KNO prediction is based upon the assumption that scaling for inclusive reactions is reached as $s \to \infty$. For the purpose of illustrating consistency with a single energy-independent form $\psi(z)$, the data of Fig. 2(a) have been fitted to an expression $\psi(z) = b \exp\left(\sum_{i=1}^{m} a_i z^i \right)$ for various values of m and for $0 \leq z \leq 3.1$. The solid curve shown in Fig. 2(a) is the result of a least squares fit with $m = 5$ (yielding an overall χ^2/number of degrees of freedom = 140/75):

$$\psi(z) = 0.085 \exp(10.3z - 13.0z^2 + 7.54z^3 - 2.27z^4 + 0.26z^5). \qquad (2)$$

Note that the use of data obtained from negatively charged beams interacting with protons or neutrons provides constraints on $\psi(z)$ for $z \leq 0$.

Figure 2(b) shows that not all data lie on this single curve. The selected data[5] range from 12 to 25 GeV/c incident beam momentum and represent six types of incident particle. Only the 15 GeV/c $\bar{p}p$ data are consistent with the solid curve, as is to be expected from Fig. 1 which indicates that only these data are consistent with $\langle n \rangle / D \simeq 2$.

The eight lowest moments of the multiplicity distributions for all data[5] consistent with $\langle n \rangle / D \simeq 2$ are shown in Fig. 3 as a function of incident laboratory momentum. Again, all of these data are consistent with

$$d_q = \frac{\langle n^q \rangle}{\langle n \rangle^q} ,$$

being independent of both the energy and quantum numbers of the incident beam particle.[8] There is, however, an indication in the data that for $q > 5$ the d_q tend to increase slowly with incident momentum. This would mean (a) that the approach to an asymptotic form may be very slow, and (b) that the present KNO function which fits the data is not the asymptotic form. In this regard, the apparent onset of the KNO form at relatively low energies should be viewed only as evidence for an independence of the final state multiplicity distribution on the initial states in high-energy collisions. The asymptotic KNO function may indeed differ[9] from the form in Eq. (2) which gives a very broad multiplicity distribution at ultra-high energies.

Furthermore, the fact that $d_q > 1$ (rather than equal to one) may imply the existence of long-range correlations in addition to the short-range correlations of Mueller-Regge theory.[3] We believe that this and the energy dependence of $\langle n \rangle / D$ presently observed in $\bar{p}p$ and in other nonannihilation interactions is suggestive of two components to the particle production process and that the apparent scaling prediction of KNO may result from a combination of a diffractive process and a multiperipheral process.

In summary, this compilation of partial cross sections from hadron-proton collisions indicates that

(a) the apparent onset of semi-inclusive KNO scaling for topological cross sections is reflected in the approach of $\langle n \rangle / D$ to a constant value (experimentally $\simeq$ 2).

(b) the constant (asymptotic ?) value of $\langle n \rangle / D$ appears to be independent of the nature of the initial state hadrons.

(c) the energy-independent function predicted by KNO also seems to be independent of the initial state at sufficiently high energies.

(d) the energy at which this scaling behavior is attained is dependent on the beam hadron; in particular, for the $\bar{p}p$ system this apparent scaling is reached at relatively low (~7 GeV/c) energies.

Furthermore, it becomes important to obtain higher energy data in order to determine whether the present trend of a constant $\langle n \rangle / D \simeq 2$ continues or whether the multiperipheral process or the diffractive particle process predominates in a two-component view, perhaps causing $\langle n \rangle / D$ to deviate[10] from 2. In this context it may be noted that the $\bar{p}p$ system is perhaps the most advantageous in that it could either indicate the trend of much higher energy proton-proton collisions or be the first to show a departure from KNO scaling.

REFERENCES

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[2] P. Olesen, Phys. Letters 41B, 602 (1972).

[3] Z. Koba, H. B. Nielsen, and P. Olesen, Nucl. Phys. B40, 317 (1972).

[4] Following the completion of this work, we received a preprint by I. Rama Rao and K. V. L. Sarma, TIFR/TH/73-14 (1973), in which they also have observed that low-energy $\bar{p}p$ data fall on the same curve as the high-energy pp data.

[5] $\bar{p}p$ Data

1.23 and 1.54 GeV/c: W. A. Cooper et al., Phys. Rev. Letters 20, 1059 (1968); Nucl. Phys. B16, 155 (1970).

2.32 GeV/c: T. Fields et al., $\bar{p}p$ Interactions at 2.32 GeV/c, to be published.

3.28 and 3.66 GeV/c: T. Ferbel et al., Phys. Rev. 137B, 1250 (1965).

5.7 GeV/c: V. Alles-Borelli et al., Nuovo Cimento 46A, 438 (1966); K. Boeckmann et al., Nuovo Cimento 42A, 954 (1966).

6.94 GeV/c: T. Ferbel et al., Phys. Rev. 173, 1307 (1968).

12 GeV/c: I. Borecka, Nuovo Cimento 5A, 19 (1971).

15 GeV/c: J. Lach and F. T. Dao, Bull. Am. Phys. Soc. 18, 694 (1973).

K^+p Data

12.7 GeV/c: S. L. Stone, Ph.D. Thesis at University of Rochester, COO-3065-17 (1972).

K^-p Data

12.6 GeV/c: T. W. Ludlam, Ph.D. Thesis at Yale University (1969).

γp Data

2.8 GeV/c and 4.7 GeV/c: J. Ballam et al., Phys. Rev. D5, 545 (1972).

π^-p Data

205 GeV/c: R. Huson, Invited talk at the Vanderbilt Conference, March, 1973, also NAL-Conf-73/30-EXP.

For pp Data, see Ref. 1, and for low-energy $\pi^{\pm}$p and pp data, see compilation by O. Cyzewski and K. Rybicki, Nucl. Phys. B47, 633 (1972).

[6]Note that for $\bar{p}p$ interactions, topological cross sections have been used with no distinction made between annihilation and nonannihilation final states.

[7]E. L. Berger, Proceedings of the Fourth International Conference on High Energy Collisions, Oxford, Vol. I, 303 (1972).

[8]It should be noted that $\langle n \rangle /D$ is related to the second moment, d_2, namely $\langle n \rangle /D = (d_2 - 1)^{-\frac{1}{2}}$.

[9]For example, if $d_q \xrightarrow[s\to\infty]{} 1$ for all q, as predicted by Mueller-Regge theory, the asymptotic $\psi(z)$ would be a delta function at $z = 1$. As another example, if we assume that at infinite energy all the d_q obey the empirical relation observed to hold for the first few d_q at present NAL energies, namely $\Delta_{q+1}/\Delta_q \to 2$ as $s \to \infty$ where $\Delta_{q+1} = d_{q+1} - d_q$, then the asymptotic form for $\psi(z)$ will consist of three delta functions located at $z = 0, 1$, and 2 respectively. We wish to thank C. Pascaud for informative discussions on this point.

[10]Some hints of a constant $\langle n \rangle /D$ (≈ 2) have been reported in cosmic-ray studies in the TeV energy region, e.g., T. Kobayashi et al., Progr. Theoret. Phys. (Kyoto) 32, 738 (1964) and S. N. Ganguli and P.K. Malhotra,

Tata Inst. preprint TIFR-BC-72-6(1972). $\langle n \rangle / D$ does not, however, describe the detailed structure of the multiplicity distribution.

FIGURE CAPTIONS

Fig. 1. Plot of $<n>/D$ versus laboratory momentum. Broken lines are drawn through data of same initial states. See Ref. 5 for compilation of data.

Fig. 2. (a) Plot of $<n> \frac{\sigma_n}{\sigma_{inel}}$ versus $\frac{n}{<n>}$ for reactions that satisfy $<n>/D = 2$.

(b) Plot of $<n> \frac{\sigma_n}{\sigma_{inel}}$ versus $\frac{n}{<n>}$ for reactions with incident momentum between 12.5 GeV/c and 25 GeV/c. The dotted curve is Slattery's fit to pp data $\geq$ 50 GeV/c and the solid curve is given in the text. See Ref. 5 for compilation of data.

Fig. 3. Plot of $<n^q>/<n>^q$ versus incident momentum for $q = 2$ to 9. The average values for the first four moments are 1.25±0.01, 1.82±0.02, 2.96±0.05, and 5.27±0.11, respectively.

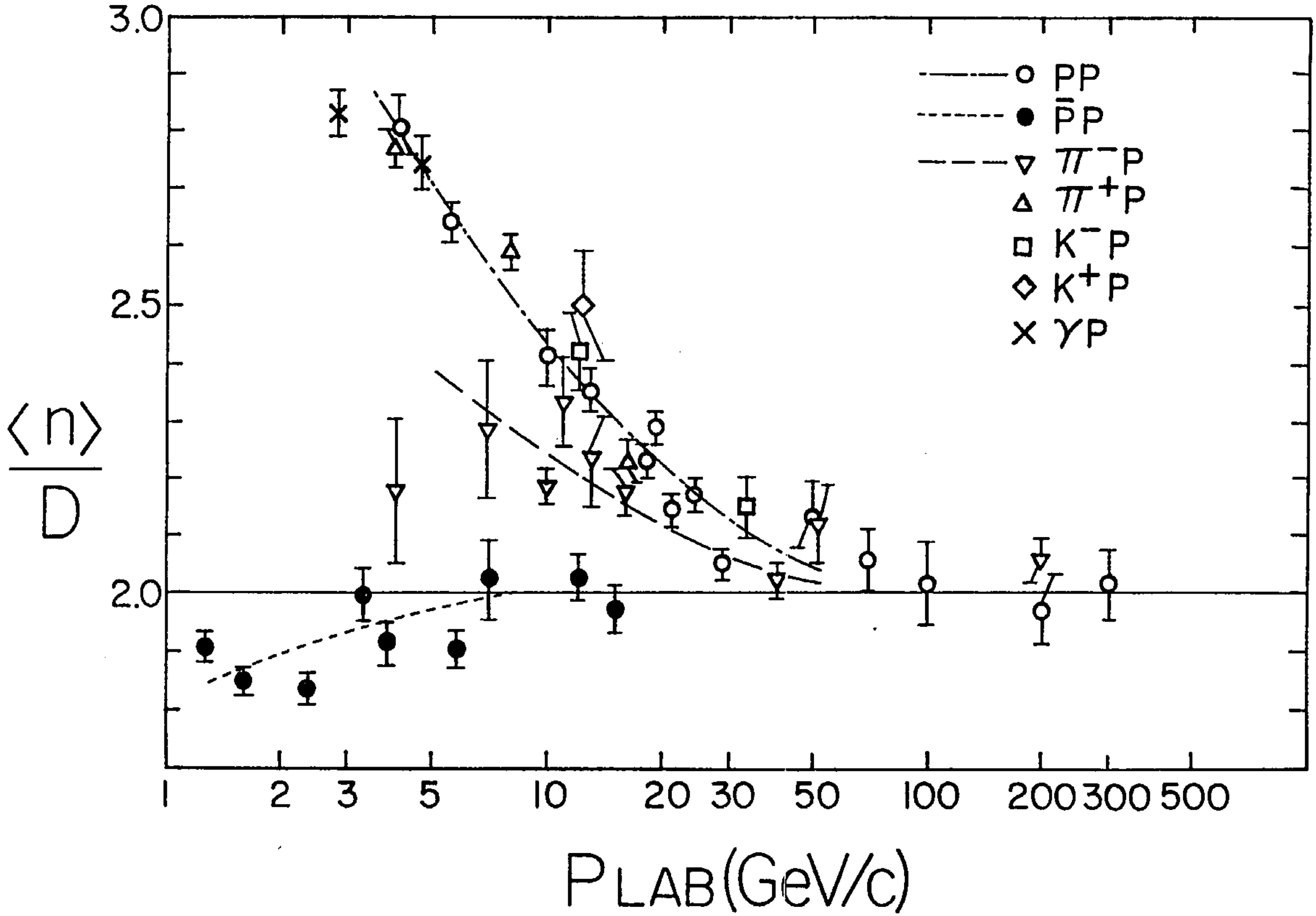
3.0
2.5
2.0
⟨n⟩/D
PP
P̄P
π⁻P
π⁺P
K⁻P
K⁺P
γP
1
2
3
5
10
20
30
50
100
200
300
500
PLAB(GeV/c)

Fig. 1

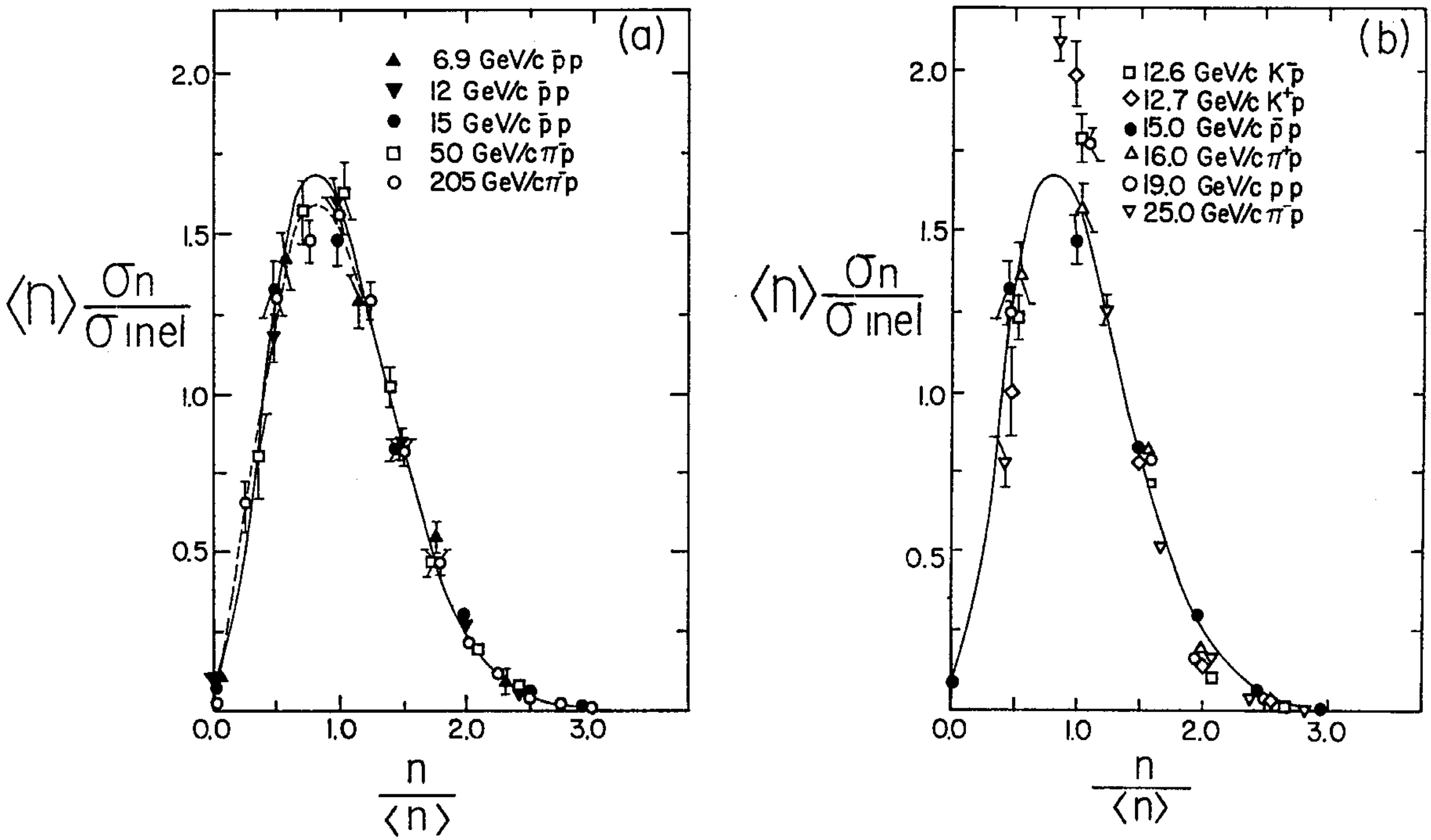
(a)
6.9 GeV/c p̄p
12 GeV/c p̄p
15 GeV/c p̄p
50 GeV/c π⁻p
205 GeV/c π⁻p
⟨n⟩ σn/σinel
n/⟨n⟩
(b)
12.6 GeV/c K⁻p
12.7 GeV/c K⁺p
15.0 GeV/c p̄p
16.0 GeV/c π⁺p
19.0 GeV/c pp
25.0 GeV/c π⁻p

Fig. 2

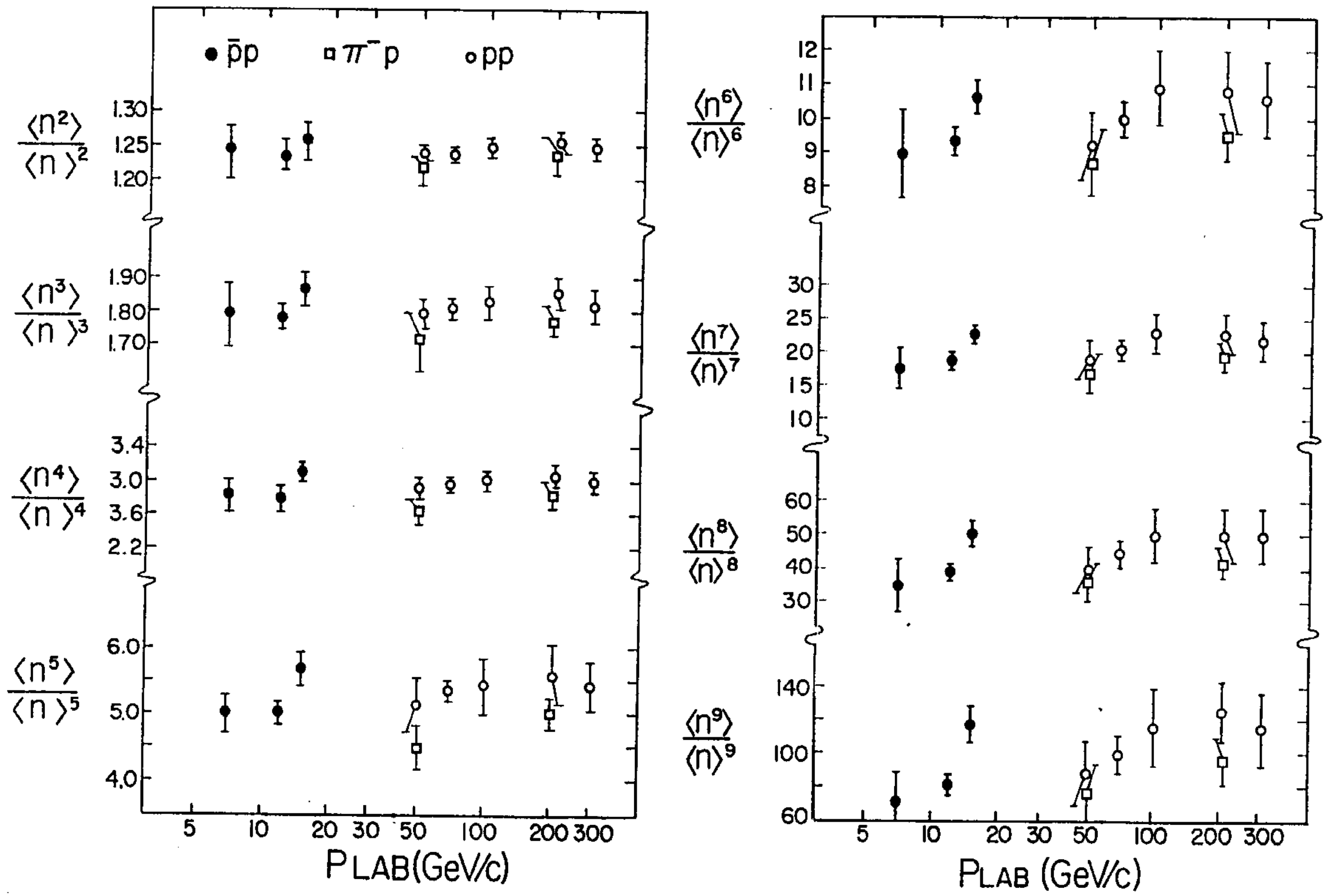
p̄p
π⁻p
pp
⟨n²⟩/⟨n⟩²
⟨n³⟩/⟨n⟩³
⟨n⁴⟩/⟨n⟩⁴
⟨n⁵⟩/⟨n⟩⁵
⟨n⁶⟩/⟨n⟩⁶
⟨n⁷⟩/⟨n⟩⁷
⟨n⁸⟩/⟨n⟩⁸
⟨n⁹⟩/⟨n⟩⁹
PLAB(GeV/c)
PLAB (GeV/c)

Fig. 3