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Energy and Multiplicity Dependence of Two-Particle Correlations in 18.5, 100, 200, and 360 GeV/c $\pi^- p$ Inclusive Reactions

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Abstract

Inclusive and semi-inclusive two-particle rapidity correlations for unlike (-+) and like (--) particle pairs have been studied at $s = 35.6$, 188, 376, and 673 GeV^2. Striking differences in both energy and multiplicity dependence are observed between like and unlike pairs. The (-+) correlations in the central region grow with $\ln s$ and increase with $1/n$ as would be expected for a simple cluster with population $< k_o^{-+} > = 1.60 \pm 0.12$ charged particles per cluster and correlation length $\delta = 0.99 \pm 0.03$. The (--) correlations show no s or n dependence and are consistent with zero except in the region $\phi < 45^o$ where Bose-Einstein effects dominate.

Previous investigations[1] have established that central-region hadrons from high energy inclusive reactions are emitted not independently, but in "clusters", correlated in the cms rapidity variable $y = 1/2 \ln[(E + p_L)/(E - p_L)]$. Two-particle rapidity correlations are known to be short-range, dependent solely on rapidity difference Δy, and, having been observed for each charge multiplicity separately, cannot be ascribed to the combinatorial effects of inclusive reactions[2,3]. There are significant differences in correlations between particle pairs of like and unlike charge, particularly when the azimuth-angle separation ϕ is small[3,4]. When the transverse momenta are approximately the same and aligned ($\phi < 45^o$) the correlation observed at small Δy for like-charged pions can be described in terms of Bose-Einstein symmetrization effects of quantum statistics[5].

Comparatively little is known about hadron clusters. Speculation that conventional resonances could account for most of the correlation observed seems to be ruled out by recent studies[6]. According to the quark-parton picture, the gluons which dominate the central region are driven by the color force to materialize as $q\bar{q}$ color singlets, which may appear as conventional resonances provided there is an appropriate wave function fit, or as clusters ("generalized resonances") if there is not. It has been suggested[7] that the fundamental cluster parameters $< k >$, the average number of charged particles per cluster, and δ, the dispersion parameter or correlation length, could be measured by simultaneously studying the energy and multiplicity dependence of rapidity correlations in the central region, $y_1 = y_2 \cong 0$.

We report the result of a systematic study of the energy and multiplicity dependence of two-particle rapidity correlations in $\pi^- p$ interactions at 18.5, 100, 200, and 360 GeV/c. The study is based on new data from 30,000 events at 360 GeV/c obtained using the Fermilab 30 in. bubble chamber/wide-gap spark chamber hybrid system, combined with previous data from 17,000 events at 200 GeV/c and 7,700 events at 100 GeV/c obtained with the same apparatus, and 7,800 events at 18.5 GeV/c obtained at BNL. Experimental procedures are described elsewhere[2,3,8].

Data at each energy were treated in a consistent manner: events were binned in a $\Delta y = y_1 - y_2$, $y_+ = y_1 + y_2$ coordinate system, in consideration of the fact that correlations are known to depend on rapidity difference. For each charge multiplicity n the single-particle densities $\rho_1(y) = \sigma^{-1} d\sigma/dy$ and the two-particle density $\rho_2(y_1, y_2) = \sigma^{-1} d^2\sigma/dy_1 dy_2$ were computed. The normalized correlation functions $R_n(y_1, y_2) = R_n(\Delta y, y_+) = [\rho_2(y_1, y_2)/(\rho_1(y_1)\rho_1(y_2))] - 1$ were then determined for each charge multiplicity. The procedure was repeated for the data at each energy.

Semi-inclusive correlations for the 360 GeV/c data are shown for the (-+) pairs and the (--) pairs respectively in Fig. 1(a) and (b). In the case of the unlike (-+) pairs, significant correlation near $\Delta y = 0$ is evident for all orders of the charge multiplicity n, and falls off approximately as 1/n. For the like-charge (--) pairs[9] correlation near $\Delta y = 0$ is less prominent, and shows no clear n dependence.

The observed n-dependence for (-+) pairs is consistent with a model[7] which assumes that clusters are emitted independently, according to the reaction

mechanism which dominates production in the central region, and decay isotropically. When the cluster multiplicity distribution is narrow,

$$R_n(0, 0)^{-+} = \frac{\ln s}{n}\left[\frac{\langle k\rangle^{-+}}{2\delta\sqrt{\pi}} - \frac{\langle k\rangle^{-+}}{\ln s}\right] \qquad (1)$$

$$R_n(0, 0)^{--} = \frac{\ln s}{n_-}\left[\frac{\langle k\rangle^{--} - 1}{2\delta\sqrt{\pi}} - \frac{\langle k\rangle^{--}}{\ln s}\right]. \qquad (2)$$

To determine the central-region correlation value $R_n(0, 0)$ with the best statistics the values of $R_n(y_1, y_2)$ along a line of constant y_+ were determined as a function of Δy, and the seven central values[10] of R_n were fitted with a Gaussian function. Fitted values of the $\Delta y = 0$ correlation peak for $y_+ = 0$ and $y_+ = \pm 0.4$ were averaged to obtain $R_n(0, 0)$ for each multiplicity, at each energy.

For the particle pairs of unlike charge, we plot the resulting $R_n(0, 0)^{-+}$ as a function of 1/n for the highest-energy data in Fig. 2(a). The energy dependence of $R_n(0, 0)^{-+}$ for $n = 8$ events is shown[11] in Fig. 2(b). The narrow-cluster model prediction, eqn. (1), provides an excellent fit to both distributions. Fitting the two distributions jointly yields the measurement of the cluster parameters: $\langle k\rangle^{-+} = 1.60 \pm 0.12$, $\delta = 0.99 \pm 0.03$. Virtually the same values are obtained from the slope and intercept of the distribution of Fig. 2(b) alone[12].

For the particle pairs of like charge, we attempt to distinguish the consequences of Bose-Einstein effects by introducting the $\phi \leq 45^\circ$ cut used in ref. 5. Fig. 1(c) shows the semi-inclusive correlations for the (--) pairs for which $\phi \leq 45^\circ$. Correlations are prominent for all orders of multiplicity, much

more so than in the total (--) sample of Fig. 1(b). For the remaining (--) pairs with $\phi > 45^{\circ}$ (not shown) there is little evidence of correlation.

To describe (--) particle pairs we introduce the function $R_n'(y_1, y_2) = R_n + (1/n_-)$, which for identical particles is zero in the absence of correlation. $R_n'(0, 0)^{--}$ is shown as a function of 1/n for $0 \leq \phi \leq 45^{\circ}$ and $45^{\circ} < \phi \leq 180^{\circ}$ pairs in Fig. 3(a). Neither distribution shows significant n-dependence, and the $\phi > 45^{\circ}$ correlations are consistent with zero for each multiplicity. The energy dependence of $R_n'(0, 0)^{--}$ for $n = 8$ events is shown in Fig. 3(b). Correlations for the $\phi < 45^{\circ}$ region show significant s-dependence in contrast to the $\phi > 45^{\circ}$ region, where correlations are consistent with zero at each energy. We conclude that there is no evidence of significant (--) correlations beyond the Bose-Einstein effect. This is consistent with a model in which the produced clusters contain predominantly two charged particles of opposite sign, and (--) correlations are due to long-range effects between clusters.

If (-+) and (--) correlations are a consequence of different mechanisms, as they appear to be, the interpretation of previous results on cluster properties based on experiments[13] in which the charges of the secondary particles could not be distinguished is open to question. In the sense that these results describe the average behavior of the (+ -) and (--) systems, they are in agreement with the results reported here. The values obtained in the present experiment, $< k >^{+-} = 1.60 \pm 0.12$ and $\delta = 0.99 \pm 0.03$, are reasonably consistent with the data of Kafka et al.[1] for pp collisions at a single energy with limited statistics.

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7. E. L. Berger, Nucl. Phys. B85, 61 (1975) and private communication.
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9. Like-charge (++) pairs were also studied in this experiment. Their correlation behavior was essentially the same as for (--) pairs, and are not further discussed.
10. In the lowest-energy data (18.5 GeV/c), where the central region is small, only 5 values of $R_n(y_1, y_2)$ were fitted.
11. The $n = 8$ topology is the smallest multiplicity for which we can ignore diffractive effects in our 360 GeV/c data, where $< n > = 8.73$, and is the largest multiplicity for which clear correlation signals can be obtained

in the 18.5 GeV/c and 100 GeV/c data, where statistics are limited. See F.T. Dao et al., Phys. Letters 45B, 402 (1973), and J.W. Lämsä et al., Phys. Rev. (to be published).

12. Berger's model for a broad (Poisson) cluster multiplicity distribution would predict (-+) correlations increasing with n, contrary to the n-dependence observed here.

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Figure Captions

Fig. 1 Semi-inclusive correlations $R_n(\pm y, y)$ as a function of $\pm y$, integrated over a central region $-4.05 \leq y_+ \leq 4.05$, for the data at 360 GeV/c. (a) Correlations for (-+) pairs. (b) Correlations for (--) pairs. (c) Correlations for (--) pairs for which the azimuthal restriction $\phi \leq 45^\circ$ is imposed.

Fig. 2 Energy and multiplicity dependence of the correlation functions for (-+) unlike-charge pairs. (a) $R_n(0, 0)^{-+}$ as a function of 1/n for 360 GeV/c interactions. (b) $R_n(0, 0)^{-+}$ as a function of s for n = 8 events.

Fig. 3 Energy and multiplicity dependence of the correlation functions for (--) like-charge pairs. (a) $R'_n(0, 0)^{--}$ as a function of 1/n for 360 GeV/c interactions. Events for which $0 \leq \phi \leq 45^\circ$. (Bose-Einstein cut) are shown as circles, $45^\circ \leq \phi \leq 180^\circ$ as crosses. (b) $R'_n(0, 0)^{--}$ as a function of s for n = 8 events, with ϕ cut as above.

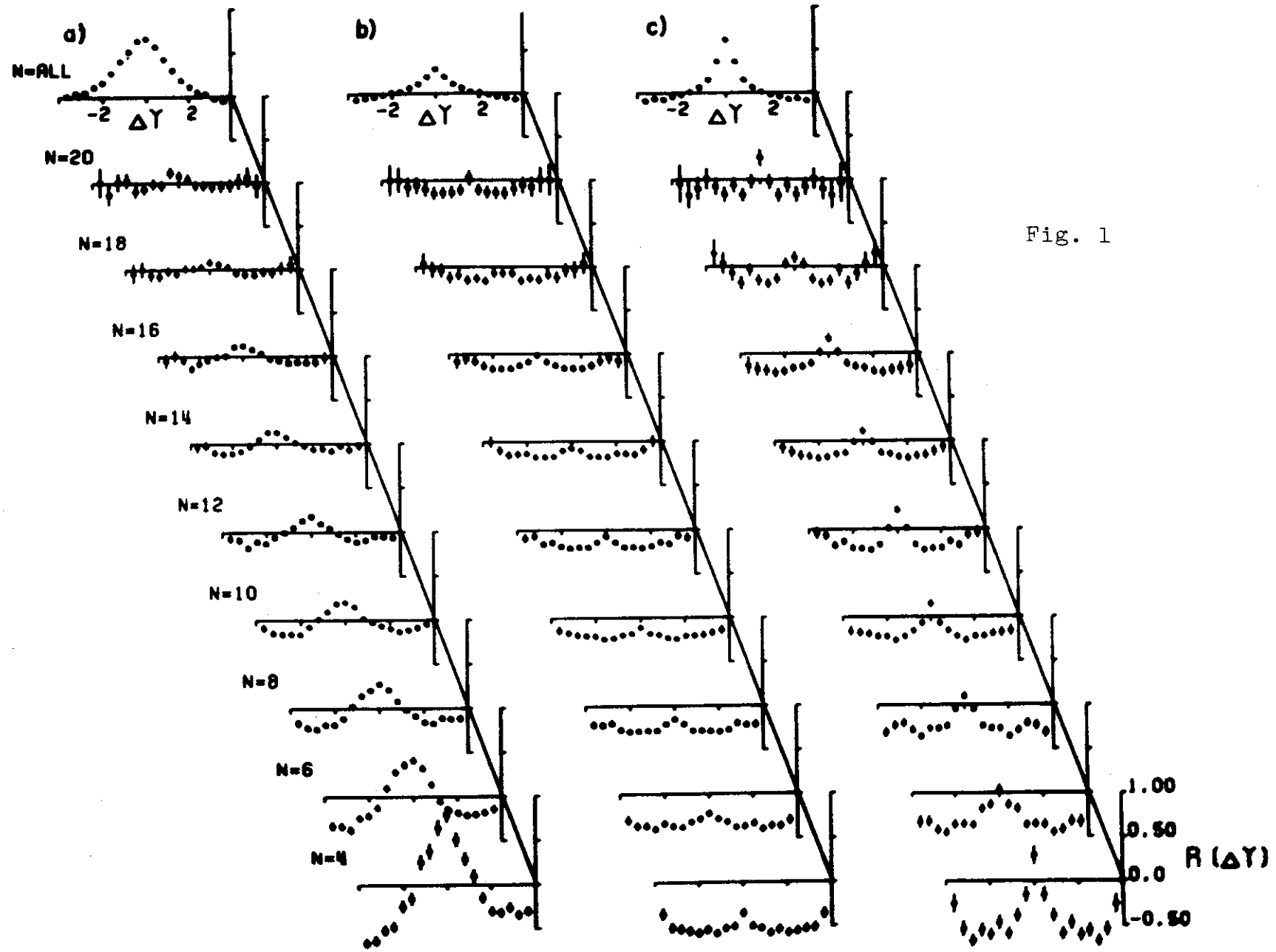
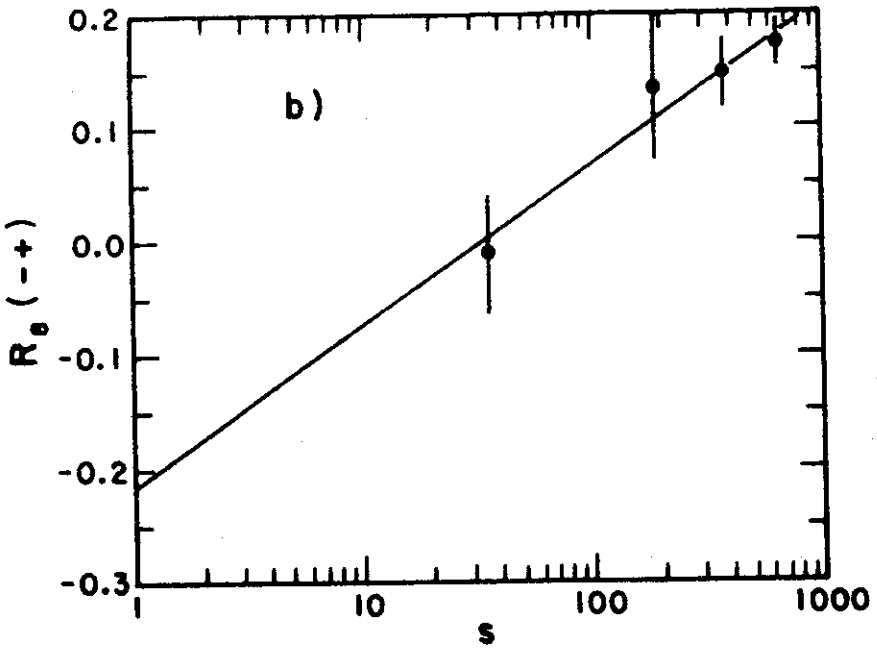


Fig. 1


b)
$R_s(-+)$
s

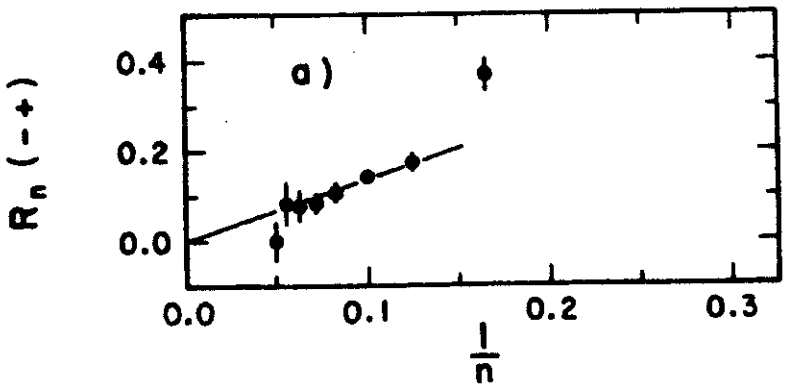
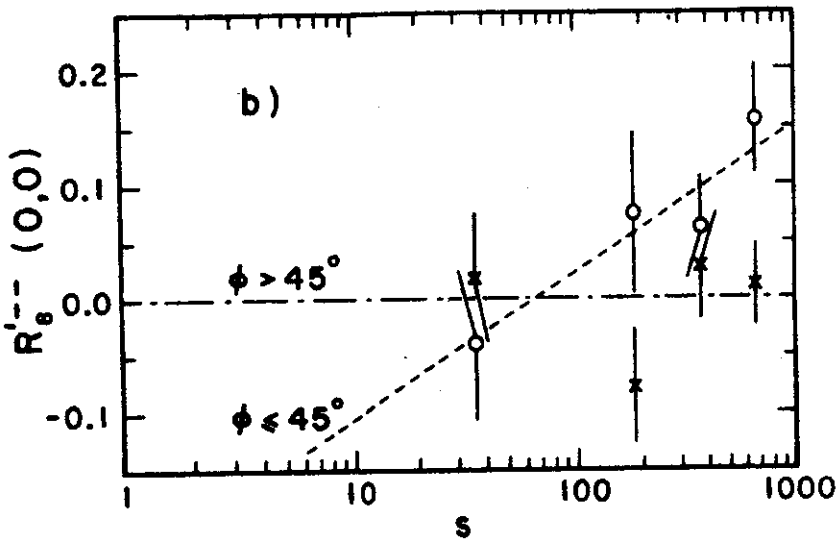

a)
$R_n(-+)$
$\frac{1}{n}$

Fig. 2


b)
$\phi > 45°$
$\phi \leq 45°$
$R'^{--}_s(0,0)$
s

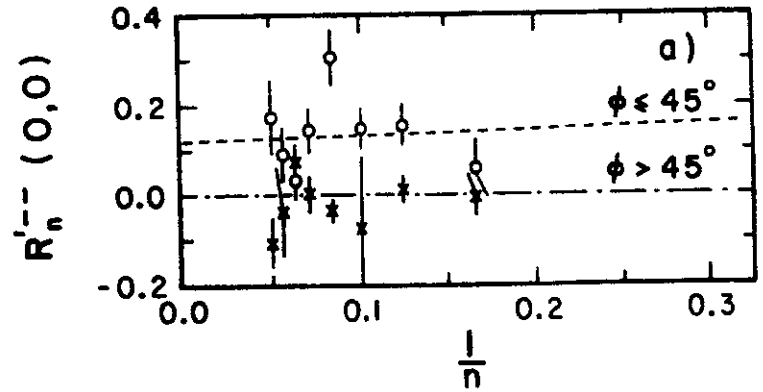

a)
$\phi \leq 45°$
$\phi > 45°$
$R'^{--}_n(0,0)$
$\frac{1}{n}$

Fig. 3