Two-Particle Correlations in Inclusive *pp* Interactions between 13 and 28 GeV/*c*

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New data are presented on π^- production in inclusive pp interactions at 13, 18, 21, 24, and 28.5 GeV/c. Mean values $\langle n\rangle$, $\langle n(n-1)\rangle$, and the associated multiplicity $\langle n(y)-1\rangle$ are given as functions of s. Single- and two-particle spectra are presented. The nova model reproduces our two-pion inclusive distributions very well and thus explains strong correlations found between π's as a simple manifestation of small inelasticity, observed previously in single-particle spectra.

Correlations among final-state hadrons produced in inclusive reactions have been stressed as an important means to identify new characteristics of multiparticle production.[1-5] Many different models reproduce observed properties of single-particle inclusive distributions[3] and predict similar growth with energy of mean multiplicity (e.g., $\langle n\rangle \sim \log s$). This is true because all models are constructed to embody, in one form or another, the three major features of single-particle spectra,[3,6] viz., scaling, a universal transverse-momentum cutoff, and small mean inelasticity of through-going hadrons (leading particle effect). However, these models predict significant differences in energy dependence of $\langle n(n-1)\rangle$ and in shapes of two-particle inclusive distributions. Indeed, fragmentation-type models[1,4,7] suggest a multiplicity distribution $\sigma_n \propto n^{-2}$ at large n; this implies that $f_2 \equiv \langle n(n-1)\rangle - \langle n\rangle^2 = c\sqrt{s}$ at large s, where c is a positive constant. In multiperipheral and other short-range-correlation models,[2,8] $f_2 \propto \log s$.

In this Letter we present and discuss new data from $pp \to \pi^-\pi^- X$ at 13, 18, 21, 24, and 28.5 GeV/c. Several features of these data indicate that the two π^-'s are produced with positive correlation and that this correlation becomes stronger as s increases. We discuss the physical significance of these correlations, both in general terms and in the context of models. The data for this study, recorded with the Brookhaven National Laboratory 80-in. hydrogen bubble chamber, come from a total of 33 168 inelastic events with four or more prongs.[9] At each momentum, there are roughly 3 μb per event. A fiducial volume cut was made to ensure accurate momentum measurements. The number of events and negative tracks used for this study are, in ascending order of incident momentum, (5246, 6750), (7073, 10 107), (8228, 12 472), (6401, 10 127), and (6220, 10 406). Possible K^- contamination has been estimated from an independent study of K_s^0 production in the same film.[10] We find this contamination to be less than 3% at any of the incident momenta.

In Fig. 1, measured values are presented for the average quantities $\langle n\rangle$, $\langle n(n-1)\rangle$, and $\langle n(n-1)\rangle/\langle n\rangle^2 - 1$. Throughout this paper, n denotes the number of π^- per inelastic collision. If the π^-'s were statistically uncorrelated, then the

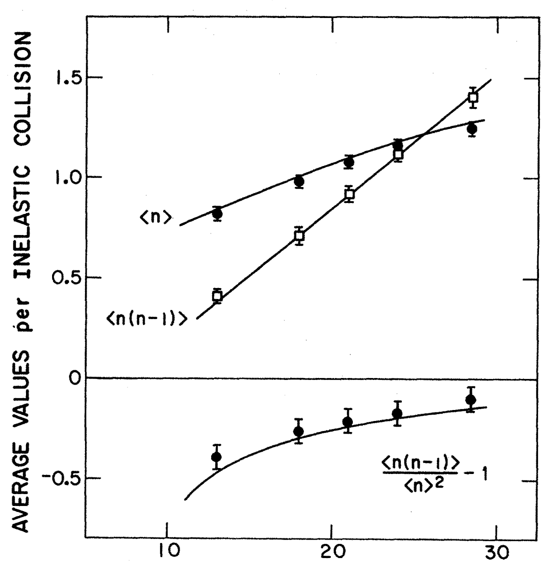

FIG. 1. Measured average values $\langle n\rangle$, $\langle n(n-1)\rangle$ and $\langle n(n-1)\rangle/\langle n\rangle^2 - 1$ plotted as functions of p_{lab}. Here n denotes number of negative tracks (π^-) per inelastic pp collision. Curves are computed from the nova model.

multiplicity distribution would obey the Poisson formula $\sigma_n \propto \lambda^n/n!$, for which $f_2 \equiv \langle n(n-1)\rangle - \langle n\rangle^2 \equiv 0$. Because of restrictions imposed by energy-momentum conservation [e.g., $n < N_0(s)$] and charge conservation, it may not be reasonable to expect a Poisson formula to be exactly valid at finite energies; further, as emphasized by Mueller in the context of a broad class of Regge models, there is no reason to expect a pure Poisson distribution on general dynamical grounds.[8] Nevertheless, the correlation parameter f_2, which is a direct measure of the non-Poisson nature of σ_n, is convenient for expressing deviations from independent-particle production. Our data show that f_2 is negative over the energy range 10–30 GeV/c, so that the multiplicity distribution is narrower than Poisson. As energy increases, the ratio $f_2/\langle n\rangle^2$ shown in Fig. 1 approaches zero.[11] Higher-energy data on $\langle n\rangle$ and f_2 are available from Serpukhov,[12] and from Echo Lake.[13] Although supporting a change in sign of f_2 from negative to positive as s increases, the errors in these data do not allow a choice between $f_2 \propto \log s$ and $f_2 \propto \sqrt{s}$.

Solid curves in Figs. 1–3 are calculations based on the nova model,[5,7] an explicit fragmentation model. For all these results, the formalism of Ref. 5 is used, with one addition: Only 70% of σ_{inel} is associated with single nova formation (σ_1) and the remaining 30% with back-to-back double nova production (σ_2). We previously determined the ratio $\sigma_2/\sigma_1 \cong 3/7$ to provide an essentially perfect representation of 18.5-GeV/c $\pi^+p \to \pi^-\pi^-X$ data.[14] If extrapolated to large s, this model predicts $\langle n\rangle \sim 0.7 \log s$ and $f_2 \propto +\sqrt{s}$.

We examine next the associated multiplicity[15]

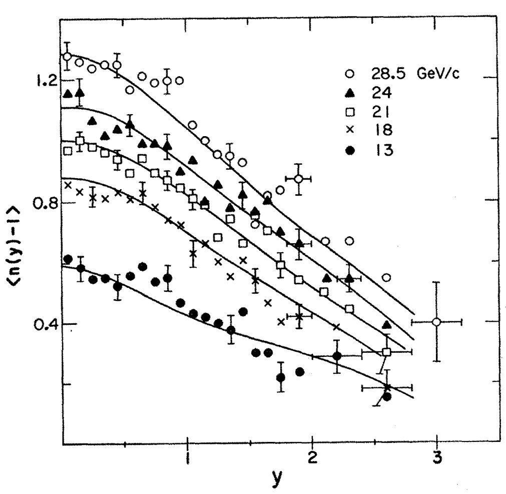

FIG. 2. Associated multiplicity $\langle n(y)-1\rangle$ versus y for each of our five momenta. See text for definition. Curves are predictions of the nova model.

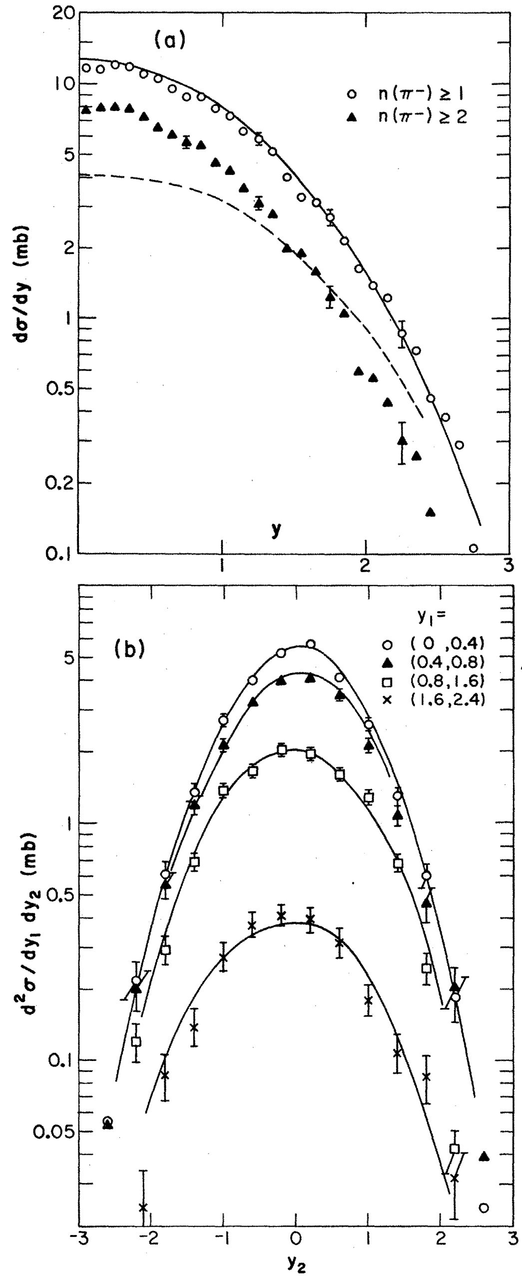

FIG. 3 (a) Inclusive single-particle rapidity distributions from $pp \to \pi^-X$ at 21 GeV/c; open circles ($d\sigma/dy$) are computed from all events contributing a π^-, whereas triangles ($d\sigma'/dy$) are obtained from events in which two or more π^- are found. The dashed curve is a smooth interpolation of the difference $d\sigma_1/dy = d\sigma/dy - d\sigma'/dy$. (b) Two-particle inclusive distribution $d^2\sigma/dy_1dy_2$ for $pp \to \pi^-\pi^-X$ at 21 GeV/c; y_1 and y_2 are rapidities of the two π^-. The distribution is plotted versus y_2 for values of y_1 in the intervals indicated. In (a) and (b), solid curves are predictions of the nova model.

$\langle n(\vec{p})-1\rangle$, defined as the multiplicity of remaining π^-'s after removal from the sample of a π^- with momentum $\vec{p}$. Thus,

$$\langle n(\vec{p}_1)-1\rangle\left(E_1\frac{d\sigma}{d^3p_1}\right)=\int\frac{E_1E_2\,d^2\sigma}{d^3p_1\,d^3p_2}\frac{d^3p_2}{E_2}. \qquad (1)$$

Here, $E\,d\sigma/d^3p$ is the single-π^- inclusive distribution, and $E_1E_2\,d^2\sigma/d^3p_1\,d^3p_2$ is the two-particle distribution. If the π^- were emitted in an entirely uncorrelated fashion, then $\langle n(\vec{p})-1\rangle$ would be independent of $\vec{p}$. Shown in Fig. 2 are our values of $\langle n(y)-1\rangle$ for all five momenta; y is the pion's (c.m.) longitudinal rapidity. Because of symmetry, we present results[16] folded about $y=0$.

In Fig. 2, the increase of $\langle n(0)-1\rangle$ with s is a reflection of the fact that $\langle n\rangle$ and all-relevant partial cross sections $\sigma_n(s)$ $(n\geqslant 2)$ are increasing over our energy range. The fall of $\langle n(y)-1\rangle$ by approximately a factor of 2 between $y=0$ and $y=2$ follows a trend expected from energy conservation. Re-expressing Eq. (1) in terms of single-particle cross sections computed from exclusive channels with $n\pi^-$, we obtain

$$\langle n(y)-1\rangle=\frac{\sum_n n(n-1)\,d\sigma_n/dy}{\sum_n n\,d\sigma_n/dy}. \qquad (2)$$

On account of energy-momentum conservation and small inelasticity, $d\sigma_n/dy$ falls off more rapidly with y for large n than for small n. This effect is illustrated in Fig. 3(a) in which are plotted both the single-particle inclusive distribution and $d\sigma'/dy$, the single-particle distribution from events in which there are at least two π^-'s. The ratio of $d\sigma/dy$ to $d\sigma'/dy$ falls from 1.5 at $y=0$ to 2.5 at $y=2$. Therefore, presence of $d\sigma_1/dy$ in the denominator of Eq. (2) but not in the numerator guarantees at least some falloff of $\langle n(y)-1\rangle$ with increasing y. This decrease has little to do with correlations in a strict dynamical sense[17] inasmuch as σ_1 cannot contribute two π^-'s.

More details concerning correlations are apparent in the two-particle rapidity distribution $d^2\sigma/dy_1\,dy_2$ [Fig. 3(b)]. Data are shown only at 21 GeV/c, but the shapes are typical of all of our energies. Observe that, as a first approximation, $d^2\sigma/dy_1\,dy_2$ peaks near $y_2=0$, essentially independently of y_1. Viewing in smaller bins, we see some tendency for $d^2\sigma/dy_1\,dy_2$ to peak at negative y_2 when y_1 is very positive (e.g., at $y_2=-0.5$ if $y_1>2.2$). These features are qualitatively similar to those observed[14,18] in $Kp\to\pi^-\pi^-X$ and in $\pi p\to\pi^-\pi^-X$. [Except that in Kp and πp, for small y_1, $d^2\sigma/dy_1\,dy_2$ peaks at positive (≈ 0.5) values of y_2, an effect associated with the well-known asymmetry of longitudinal spectra in meson-induced reactions.[3]] In Fig. 3(b), the fall of $d^2\sigma/dy_1\,dy_2|_{y_2=0}$ with increasing y_1 is approximately the same as that of $d\sigma/dy_1$ and, although the width in rapidity of $d^2\sigma/dy_1\,dy_2|_{y_1\approx 0}$ is narrower than that of $d\sigma/dy_1$, it compares satisfactorily with that of $d\sigma'/dy$ shown in Fig. 3(a). In summary, except for normalization, the y_2 dependence of $d^2\sigma/dy_1\,dy_2$ is approximately independent of y_1. There seems to be no evidence for dynamic two-π^- clustering, beyond that which can be ascertained from properties of single-particle inclusive spectra.

This latter conclusion is strengthened by comparison of the nova model with our data.[5,7] Theoretical curves shown in Figs. 1–3 are in essentially perfect agreement with data. Normalizing to the observed total inelastic cross section at 21 GeV/c, we find that the model reproduces properly the values of $\langle n(n-1)\rangle$ and $\langle n\rangle$ as functions of s, and we obtain the correct normalization, shapes, and s dependence of $\langle n(y)-1\rangle$, $d\sigma/dy$ and $d^2\sigma/dy_1\,dy_2$. Besides energy conservation, the essential ingredients of the nova model are the well-known (Gaussian) cutoff on p_T and small mean inelasticity of leading particles,[3,6] inserted in a simple framework which gives rapid scaling properties. The importance of these established properties of single-particle spectra is thus confirmed by correlation data in that these properties are sufficient to reproduce two-particle spectra also. Small inelasticity (leading particle effect) is an especially important constraint. Reproducing the correct single-particle p_T distribution is also important. Models in which $\langle p_T\rangle$ is too small (large) will predict too little (too much) correlation in y. The nova model used here reproduces correctly both the p_T and y behavior of $d^2\sigma/dy\,dp_T^{\,2}$. The relatively flat nature of the proton (single-particle) longitudinal spectrum implies that a through-going proton releases on the average $<50\%$ of its initial energy for particle creation and kinetic energy of produced particles. Consequently, individual events show clustering of particles in rapidity, with clusters tending to follow the beam or target particle in the c.m. system.[19] Our inclusive two-particle data probe this clustering in an average way.

For $p_{\text{lab}}\gtrsim 200$ GeV/c, dominance of two-particle distributions and $\langle n(y)-1\rangle$ by just a few strongly s-dependent σ_n should no longer be the case. Significant $\pi^-\pi^-$ correlations may emerge in this higher range of energies and point to as yet unidentified characteristics of multiparticle production amplitudes, such as a clustering or anticlustering tendency superimposed on properties demanded by small mean inelasticity. As discussed above, measurement of the s dependence of f_2 in this higher energy region is also crucial.[11]

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[11] In multiperipheral models, $f_2\langle n\rangle^{-2} \propto (\log s)^{-1} \rightarrow 0$ as s increases; in fragmentation models, $f_2\langle n\rangle^{-2} \propto \sqrt{s} \times (\log s)^{-2} \rightarrow +\infty$. For this reason we plot $f_2\langle n\rangle^{-2}$ rather than f_2 itself.

[12]Soviet-French Collaboration, to be published. From prong cross sections in this preprint, we compute $\langle n^-\rangle = 1.81 \pm 0.11$ and $f_2 = 0.37 \pm 0.18$. These errors are probably too conservative inasmuch as σ_m is not given for $m > 14$ prongs.

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[17]Intuitive notions regarding correlations, based on analogy with a gas or liquid (cf. Ref. 2), can be misleading over our energy range where $\langle n\rangle$ is of order unity. We note that over our energy range σ_1 (4 prongs) is the dominant partial cross section. By contrast, in a real gas $d\sigma_1/dy$ would be vanishingly small, corresponding to contributions to the particle density from ensembles in which there is only one particle.

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Search for Doubly Charged Weak Currents through $K^+ \rightarrow \pi^- e^+ \mu^+$†

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We present results of a search for the decay mode $K^+ \rightarrow \pi^- e^+ \mu^+$ which requires doubly charged weak currents for its existence. Limits are also obtained on the branching ratios for the decay modes $K^+ \rightarrow \pi^+ e^+ \mu^-$ and $K^+ \rightarrow \pi^+ e^+ e^-$. We give a comparison of some present experimental limits on neutral and doubly charged weak currents.

It has been recognized for some time that there are three alternative schemes of assigning lepton numbers and specifying lepton-number conservation[1-3] which are consistent with all of the experimental information now available on weak interactions. Leaving aside the so-called "multiplicative" scheme,[3] which is not immediately relevant here,[4] the two additive schemes differ in that (i) the usual scheme[1] assigns $L_\mu = +1$ to μ^- and ν_μ, $L_\mu = -1$ to μ^+ and $\bar{\nu}_\mu$, $L_e = +1$ to e^- and ν_e, $L_e = -1$ to e^+ and $\bar{\nu}_e$, and assumes both $\sum_j L_{uj}$ and $\sum_j L_{ej}$ to be separately conserved; whereas (ii) the alternative scheme[2] assigns $L = +1$ to e^-, μ^+, and ν and $L = -1$ to e^+, μ^-, and $\bar{\nu}$, and assumes only