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PHYSICAL REVIEW D VOLUME 10, NUMBER 9 1 NOVEMBER 1974

Two-pion correlations in pp collisions at 102 GeV/c*

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(Received 28 May 1974)

We have measured two-pion correlations in rapidity and transverse momentum in pp collisions at 102 GeV/c. The correlations, which are highly sensitive to the charges of the pions, display a behavior consistent with that expected on the basis of the short-range-order hypothesis, and, when compared with a model which does not contain explicit correlations, suggest the presence of substantial dynamic correlations in the data.

Several studies of longitudinal- and transverse-momentum correlations between particles produced in high-energy collisions have recently appeared in the literature.[1] The results of these investigations of inclusive reactions have often been somewhat difficult to interpret because these experiments have suffered from either (1) the fact that correlations, particularly at low energies, tend to be strongly influenced by the requirements of momentum-energy conservation, or (2) the fact that the measurements did not provide a comparison of correlations between different types of particles. In this paper we discuss the nature of transverse and longitudinal correlations between two π^+, between two π^-, and between π^+ and π^- mesons produced in pp collisions at 102 GeV/c. Preliminary results from this experiment, conducted in the 30-in. bubble chamber at the Fermi National Accelerator Laboratory (FNAL), have been published elsewhere.[2] The present data are from a measurement of a complete sample of ≈ 1800 events (all topologies) and an additional sample of ≈ 1200 events from the <10-pronged topologies.

The specific reactions we consider are the following:

$$pp \to \pi^+\pi^- + \text{anything}, \tag{1}$$

$$pp \to \pi^- \pi^- + \text{anything}, \tag{2}$$

$$pp \to \pi^+ \pi^+ + \text{anything}, \tag{3}$$

$$pp \to \pi^c \pi^c + \text{anything}, \tag{4}$$

where reaction (4) refers to the production of pions of either positive or negative charge. [For clarity we will often label reactions (1)–(4) according to the relevant charges of the pions, e.g., reaction (1) will be referred to as reaction (+−), etc.] In this study all negative particles are assumed to be π^- mesons, while all positive particles having momenta in excess of 1.2 GeV/c in the laboratory frame are assumed to be π^+ mesons. (Below 1.2 GeV/c protons can be separated from π^+ mesons through their ionization properties in the bubble chamber.) Because of the presence of a sizable proton contamination in the data at large rapidities ($y = \frac{1}{2}\ln[(E+p_l)/(E-p_l)]$, with E and p_l being the energy and longitudinal momentum of the particle in the center-of-mass frame), we have imposed an additional cutoff on the value of $|p_l| \le 4$ GeV/c for our accepted sample of pion-production data for reactions (1)–(4). These restrictions do not markedly affect the true pion-production cross section, but serve to reduce the proton contamination in the data to ≈10% for $y_{\pi^+} \gtrsim 0$. [There is also a small K^+/K^- and e^+/e^- contamination in reactions (1)–(4) which we ignore.[3]]

In addition to the nonpion background, the data at large positive y values suffer from momentum measuring errors; this is particularly true when both pions in reactions (1)–(4) are in the forward hemisphere of the center-of-mass frame. To improve the experimental resolution in our study of two-pion rapidity correlations, we have made use

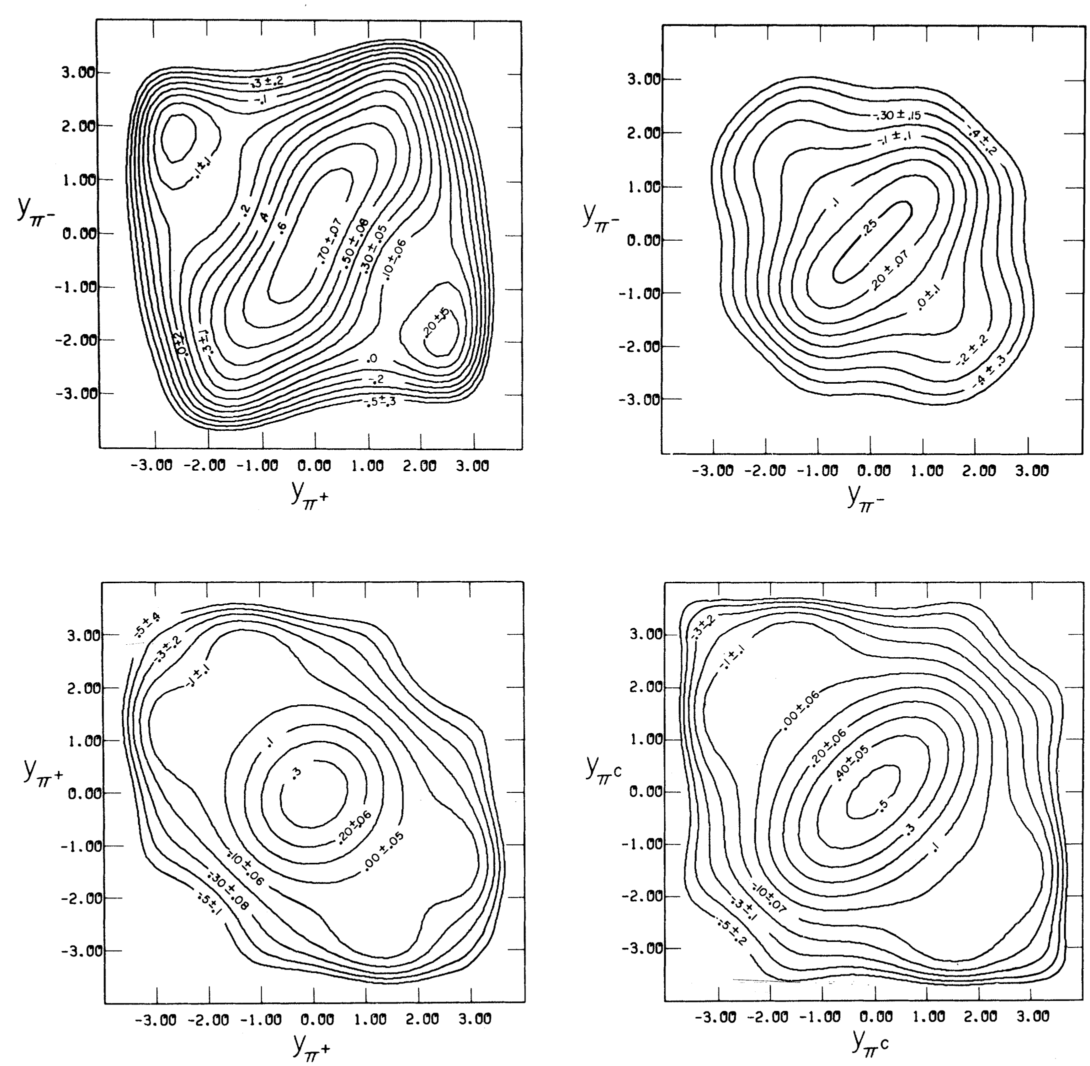

FIG. 1. Fitted contours of constant correlation density $R(y_1, y_2)$ for the two-pion production reactions (1)–(4).

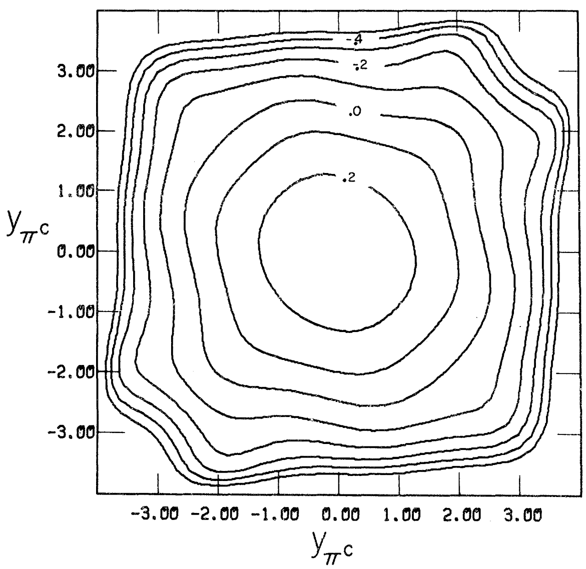

FIG. 2. Fitted contours of constant correlation density $R(y_1, y_2)$ for the Monte Carlo simulation of reaction (4).

of the symmetry of the pp incident channel, and reflected all well-measured data about the expected axes of symmetry. Specifically, the regions of rapidity used for these studies were $y_{\pi^+} \leq 0$ (no selection on y_{π^-}) for reaction (1) and $y_1 + y_2 \leq 0$ for reactions (2)–(4).

To facilitate comparison of our measurements with those at the CERN Intersecting Storage Rings (ISR)[4] and at FNAL,[5] we discuss pion-pion longitudinal-momentum correlations in terms of the two-dimensional density function $R(y_1, y_2)$:

$$R(y_1, y_2) = \sigma_{\text{inel}} \frac{d^2\sigma}{dy_1 dy_2} \Big/ \frac{d\sigma}{dy_1} \frac{d\sigma}{dy_2} - 1 , \qquad (5)$$

where σ_{inel} is the total pp inelastic cross section at 102 GeV/c.[6] Due to poor statistics we have integrated reactions (1)–(3) over all transverse momenta (p_T). The data in the (y_1, y_2) plane were fitted with exponential polynomials of tenth order: $\exp[P(y_1, y_2)]$, where $P(y_1, y_2)$ contains all terms of the form $y_1^n y_2^m$ with arbitrary coefficients, for $(n+m) \leq 10$. The fits were constrained to approach $R = -1$ near the kinematic boundaries ($|y| \approx 4$). The χ^2 probabilities for all the fits were excellent, and the results of these fits are shown in Fig. 1 in terms of contours of constant R. There is an approximately 6% uncertainty of the value of $1+R$ when both pions are in the central region of the rapidity plot ($|y| \lesssim 1.5$); this includes a 3% systematic uncertainty on the value of σ_{inel} (typical errors are shown on the contours). The errors are statistics limited outside of the central region and vary between 10% and 50% of the value of $1+R$. For acceptable χ^2 values, the order of the polynomial used in the fit does not markedly affect the results shown in Fig. 1, except for the outermost contours. For comparison, we present in Fig. 2 the contours of $R(y_1, y_2)$ for reaction (4), which are expected on the basis of a pion-production model discussed previously in the literature.[2]

This model uses as input the known charged-particle multiplicity spectrum, and the observed single-particle inclusive and semi-inclusive differential cross-section properties. Hence, although the model contains, implicitly, correlations among produced particles provided through these input characteristics, there are no explicit correlations or resonance features introduced in the calculations. Consequently, deviations of R from expectations due to the model can be taken to provide a measure of resonance or of multiparticle-cluster production in the data. The shape of the typical R contour plot, based on the pion-production model, is shown in Fig. 2. Although the magnitudes of the predicted R values depend on the charges of the pions, the shapes of the contours are essentially independent of the pion charges. In Table I we present a comparison of the experimental values of $R(0,0)$ with the predictions of our model.

Comparing the features of the data in Fig. 1 with those of the model given in Fig. 2, the following remarks apply:

(1) Significant charge-dependent differences in R are observed for reactions (1)–(3). Much of the interesting structure and quality of R observed in the individual reactions is lost when there is a summation over all charges [as in reaction (4)].

(2) There is a clear elongation of the R contours approximately along values of constant $\Delta y = |y_1 - y_2|$ for reactions $(+-)$ and $(--)$. [The slight tilt of the contours relative to the $\Delta y = 0$ axis in reaction $(+-)$ is an interesting feature, presumably reflecting the predominance of π^+ production over π^- production, even near $y = 0$.]

(3) The values of R tend to drop rapidly and become negative as Δy increases. In reactions $(+-)$ and $(++)$, however, there is some evidence for a modulation in this decrease of R (and, in fact, even for the presence of a secondary maximum in R) when the values of Δy are nearly maximal.

(4) The absolute values of R for small Δy are

Table I. Fitted values of $R(0,0)$.

Reaction	$R(0,0)$ Data	Model
$(+-)$	0.78 ± 0.06	0.45
$(--)$	0.28 ± 0.06	0.19
$(++)$	0.38 ± 0.05	0.07
(cc)	0.55 ± 0.05	0.28

considerably larger than expected on the basis of our pion-production model.

From these observations we may conclude the following:

(1) Short-ranged (small Δy) correlations are evident in the data in that R values are larger than expected for small Δy, and appear to be approximately y-independent for the central region of pion production.[7] These statements are particularly well supported by the results of reactions (+−) and (−−).

(2) Possible long-ranged (large Δy) correlations may be apparent, particularly in reaction (+−), where a secondary maximum in R occurs when $y_{\pi^+} \approx -y_{\pi^-}$ at large y values. This correlation could partially be due to the presence of a simultaneous dissociation of the two incident protons.[8]

(3) It is somewhat surprising that the elongation of the contours along constant Δy, observed in reaction (−−), is absent in reaction (++). However, a long-ranged type of correlation (arising from diffractive processes) might be expected to be more important in reaction (++) than in reaction (−−), and this difference in the two channels may qualitatively explain the lack of the elongation of the R contours in data from reaction(++). That is, there could be an overlap of comparable short-ranged and long-ranged correlations near $y \simeq 0$ which would tend to increase the overall value of R and mask the elongation of the contours.

In addition to two-particle correlations in rapidity we have also examined the dependence of correlations between transverse momenta in reactions (1)–(3). We define an azimuth ϕ between two transverse momenta as follows[1]:

$$\cos\phi = \frac{\vec{p}_{T1}\cdot\vec{p}_{T2}}{p_{T1}p_{T2}} \ . \tag{6}$$

The distribution in ϕ is expected to be peaked near 180° due to requirement of momentum conservation. The data for reaction (+−) do, in fact, have this feature.[2] The distributions for reactions (−−) and (++), integrated over all y, are, on the other hand, far more isotropic in ϕ. In Fig. 3 we display the dependence of the asymmetry in the ϕ spectrum (A_ϕ), for events with six or more charged particles in the final state, as a function of Δy, and as a function of the average value of p_T of the two pions ($\langle p_T\rangle$) for different Δy and different $\Delta p_T = \left||\vec{p}_{T1}| - |\vec{p}_{T2}|\right|$. The asymmetry is defined as follows:

$$A_\phi = \left(\int_{\pi/2}^{\pi} \frac{d\sigma}{d\phi}\,d\phi - \int_0^{\pi/2} \frac{d\sigma}{d\phi}\,d\phi\right) \Big/ \int_0^{\pi} \frac{d\sigma}{d\phi}\,d\phi \ . \tag{7}$$

Results of Fig. 3 illustrate that A_ϕ is a strong function of charge for small Δy, particularly when Δp_T is also small [data from reactions (−−) and

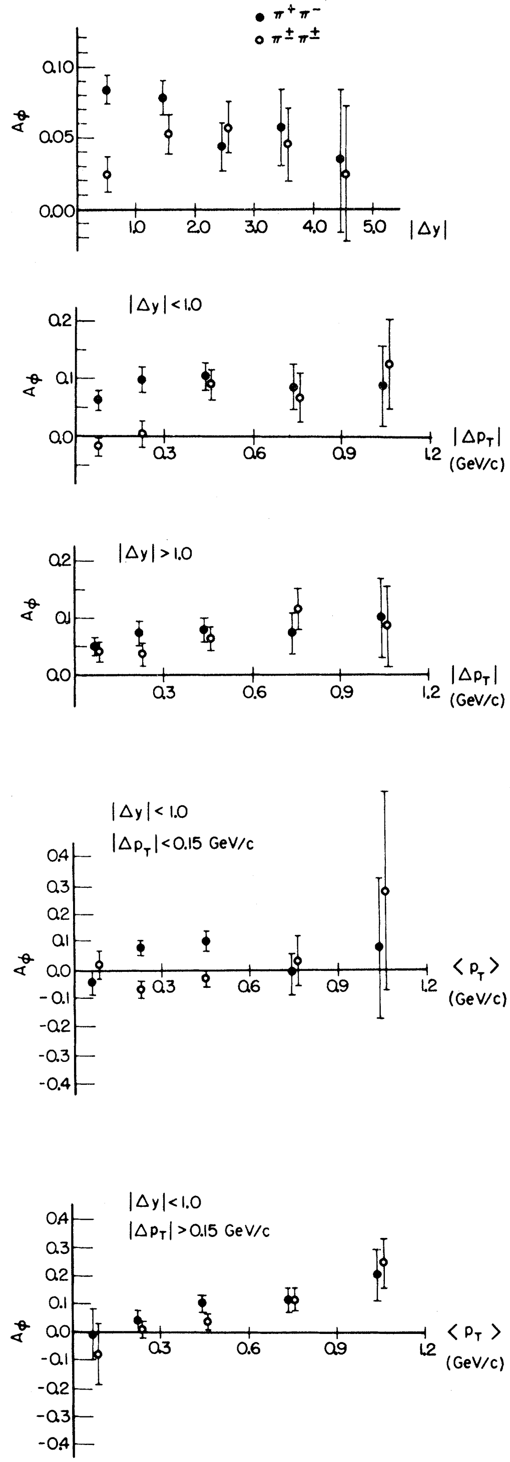

FIG. 3. Transverse asymmetries (A_ϕ) for reaction (1) (solid points) and for the sum of reactions (2) and (3) (open circles), as a function of the rapidity difference ($|\Delta y|$), the transverse momentum difference ($|\Delta p_T|$), and the average of the magnitudes of the transverse momenta ($\langle p_T\rangle$) of the two pions. Only events with six or more charged particles in the final state are used.

(++) were consistent with one another and the results were combined to improve statistics]. However, as Δy increases, A_ϕ becomes independent of charge. The p_T dependence of A_ϕ for $\Delta y > 1$ (not shown) is similar to that observed for events having $\Delta y < 1$ and $|\Delta p_T| \gtrsim 0.15$ GeV/c. Furthermore, for small Δy, A_ϕ is not only a function of the charge, but also of the value of $|\Delta p_T|$. (The increase in A_ϕ when $|\Delta p_T|$ or $\langle p_T \rangle$ becomes large may partially be due to the important influence of overall momentum conservation.)

The short-ranged anticorrelation in ϕ for reaction (+−) can be attributed to a requirement of local transverse-momentum conservation for particles which are strongly correlated in longitudinal rapidity space. The smaller anticorrelation in ϕ observed in reactions (− −) and (++) [and possibly the diminution in correlation for reaction (+−) at large Δy values] may be accounted for through the fact that a relaxation of the requirement for local transverse-momentum conservation is expected when the produced particles are not strongly correlated in rapidity. (If the production process is visualized as a multiperipheral chain, then it would be expected that $\pi^+\pi^-$ pairs would tend to be neighbors and consequently correlated in y and anticorrelated in ϕ.)

We can summarize our conclusions as follows: We have observed strong dynamic correlations for small rapidity differences between produced pions in pp collisions at 102 GeV/c. The nature of these correlations depends on the charges of the produced pions, but is rather insensitive to the collision energy.[4,5] Positive correlations in longitudinal momenta tend to be associated with anticorrelations in transverse momenta. Although the general features of the data can be understood on the basis of a multiperipheral mechanism, through a resonance production model, or simply through the production of low-mass multipion clusters,[9] a detailed understanding of the correlations would require more extensive model calculations.

We thank the FNAL Neutrino Laboratory Group and the Liaison Staff for assistance in the taking of the film exposure. We also thank E. Berger for his comments on the manuscript.

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*Research supported by the U. S. Atomic Energy Commission.

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[3]Assuming that the K^+ and K^- cross sections are comparable with that for K_S^0 production, we estimate about 5% kaon contamination in the data. The e^+ and e^- contamination from π^0 Dalitz decays is approximately 1%. See J. Chapman *et al.*, Phys. Lett. 47B, 465 (1973).

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[7]We wish to point out that the invariant mass of two pions (M) can be written as a function of Δy through the following relationship:

$$M_{12}^2 = m_1^2 + m_2^2 + 2\mu_1\mu_2\cosh(\Delta y) - 2p_{T1}\,p_{T2}\cos\phi_{12},$$

$$\mu^2 = p_T^2 + m^2.$$

Consequently, for small p_T we see that lines of constant Δy correspond to fixed M_{12}. Hence the short-ranged correlations may be interpreted as resulting from the fact that the cross section for the production of two-pion systems of fixed mass is independent of rapidity. That is, the two-pion mass spectra are independent of the rapidity of the two-pion system. It should be also noted that the diffractive component in pion production can contribute significantly to R even at $y_1 = y_2 = 0$ [see M. Le Bellac, H. I. Miettinen, and R. G. Roberts, Phys. Lett. 48B, 115 (1974), and R. Singer *et al.*, *ibid.* 49B, 481 (1974)]. We have not attempted to separate the diffractive and nondiffractive effects in the data.

[8]We note that because our data involve only correlations among pions, the secondary maximum in R is qualitatively different from a similar effect attributed to single-diffraction events in the ISR data (Ref. 4). The interpretation of our result as being due to simultaneous dissociations of the incident protons is subject to some doubt, however, because we observe that a large fraction of the four-pronged events in this region involve apparent charge exchange across $y = 0$. For the effect of momentum conservation on this particular region of (y_1, y_2) space, see Ref. 9.

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