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Recently, the study of single-particle inclusive spectra has become a popular means of probing the dynamics of high-energy multiparticle production. The study of correlations between particles is a natural step beyond single particle spectra in investigating these dynamics. Such studies can probe the nature of individual particle production in longitudinal momentum phase space. Inclusive single particle spectra have shown that the longitudinal momentum distributions of produced pions roughly follow the phase distribution dx/x[1] while the leading particles are produced with larger longitudinal momentum on the average. The transverse momentum of both leading and produced particles is severely limited compared to what is allowed by transverse phase space.

While the produced pions' longitudinal momentum distributions sum together to produce the dx/x distribution in single particle spectra, it is not known whether each individual produced pion has this same distribution or whether each individual pion has a different longitudinal momentum spectrum, which, when added together with the other pions, results in the inclusive dx/x distribution. Different dynamical models predict different behavior. The Feynman gas or pronization model predicts the former situation, while the multiperipheral, diffraction disassociation, and multifireball models (to name a few) predict the latter behavior. For example, the multiperipheral model predicts sequential pion emission in the t-channel resulting in the ordering of the longitudinal momentum of the produced pions in approximately equal intervals in rapidity.[2] Only when the individual pions' longitudinal momentum spectra are summed to form the single particle spectrum, does this model yield the smooth dx/x distribution. Investigation of the dependence of correlations between particles on their difference in longitudinal momentum can probe the nature of the individual pions' longitudinal momentum distribution and, thus, help reveal the dynamics of multiparticle production.

The mechanisms for pion production discussed above fall into two general catagories: those in which the pions are produced independently of the leading particles, and those that more or less associate each of the produced particles with one or another of the leading particles.

In the latter case, the pions that are associated with a particular leading particle are produced with similar longitudinal momentum to the leading particle while, in the case of unassociated pion production, each produced secondary will have no favored direction in the center of mass frame and will tend to populate longitudinal momentum phase space more or less evenly.

A general prediction of associated models (models that predict associated pion production) is that particles associated with different leading particles (including the leading particles themselves) will tend to become uncorrelated with each other as the energy increases, becoming completely uncorrelated at extreme energies.[3] For unassociated models, leading as well as produced particles will retain long-range correlations even at extreme energies.

An often used measure of the correlation between two particles is the distribution of the transverse angle

$$\varphi = \cos^{-1}(\vec{q}_i \cdot \vec{q}_j / |\vec{q}_i||\vec{q}_j|), \qquad (1)$$

between them. Here $\vec{q}$ is the component of the particle's momentum transverse to the beam direction. Particles that are uncorrelated will produce an even distribution in φ.

Unassociated models will predict asymmetric distributions about $\varphi = 90^\circ$, peaking at $\varphi = 180^\circ$. This behavior is mainly due to transverse-momentum conservation which requires that each particle be produced in the opposite direction from the others, on the average. Associated models overcome this effect by preferentially conserving transverse momentum locally with neighbors of similar longitudinal momentum.[4]

At low enough energies, all models predict the same results, namely, the correlations predicted by momentum and energy conservation. However, with increasing energy the predictions will begin to differ, and at extreme energies associated models will completely uncorrelate particles with sufficiently dissimilar longitudinal momenta, while unassociated models will still retain the long range correlations of momentum and energy conservation.

In order to get an idea of the energies required to differentiate the predictions of the two classes of models, we have selected a specific model from each of the two categories and calculated the transverse-angle distributions between the two final-state nucleons in pp interactions for several laboratory beam momenta.[5] From the first group we take the multiperipheral model of Chew and Pignotti,[6] as modified by Chan, Loskiewicz, and Allison,[7] in which the basic mechanism is peripherality. As an exchanged meson propagates from the fast incident particle to the target, it sequentially emits pions in the beam direction in order to lose its high momentum and be absorbed by the target at rest in the laboratory. As mentioned above, this process of sequential pion emission results in the ordering of the longitudinal momentum of the pions in approximately equal intervals in rapidity.[2] As discussed in Ref. 7, the matrix element squared for this model can be expressed as

$$|M_n(S,t)|^2 = c\prod_{i=1}^{n-1} \left(\frac{b+s_i}{b}\right)^{2\alpha_i(t_i)} \beta_i^{\,2}(t_i). \qquad (2)$$

Here the s_i and t_i are, respectively, the squares of the subenergies and four-momentum transfers corresponding to the links in the multiperipheral chain. As advocated in Ref. 7, the constant b is introduced to allow the s_i dependence to reduce to phase space for small subenergies. In all cases we have taken its value to be 1 GeV^2. The $\alpha(t)$ were taken to be the effective ρ-meson trajectory determined by Fox.[8] The $\beta^2(t)$ are taken to be simple exponentials, $\beta_M^{\,2}(t)=e^{at}$ for pion production and $\beta_N(t)=e^{bt}$ for leading nucleons.

As an example of an unassociated model, we take a pionization model (Feynman gas model) where the final-state nucleons emerge peripherally with relatively large elasticity and small transverse momentum. Each of the pions is produced with limited transverse momentum while the longitudinal momenta are equally distributed in the available longitudinal phase space. These properties are characterized by the matrix element squared

$$|M_n|^2 = \exp[g(t_1+t_n)-b\sum_{i=2}^{n-1} |\vec{q}_i|^2]. \qquad (3)$$

Here n is the number of particles in the final state, t_1 and t_n are the four-momentum-transfers squared from the incident particles to the leading elastic particles, and the $\vec{q}_i$ are the components, transverse to the beam direction, of the (n - 2) produced pions' momenta.

The two parameters in each model were adjusted to reproduce the experimental transverse-momentum distributions for the pions and protons separately, in the reaction $pp \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ at 23 GeV/c. For calculations at other momenta, the parameters of the multiperipheral model were held fixed while those of the pionization model were adjusted to give the same transverse-momentum distributions as the multiperipheral model.[9]

Figure 1 summarizes the transverse-angle distributions between the final-state nucleons for both models by plotting their backward-forward asymmetry in the reactions $pp \rightarrow pp(N\pi)$ ($N = 4, 6, 8$) for several beam momenta. For comparison, the asymmetry is also shown for inclusive reaction $pp \rightarrow pp+$ anything using the multiperipheral model of Ref. 3.[10]

Inspection of Figure 1 reveals several interesting results. As expected from the qualitative discussion above, as the energy increases the multiperipheral model predicts the protons to become less correlated, approaching almost zero correlation at 400 GeV/c. On the other hand, the pionization model retains substantial correlation at these highest energies. Thus, especially at the higher energies considered($\sim$100 GeV/c), this test seems to clearly separate the predictions of the two classes of models. Another interesting result is the independence on multiplicity of the long range correlations predicted by the multiperipheral model. Especially at the higher energies, the predictions for the different multiplicities, as well as the inclusive predictions (which include all multiplicities), are very nearly the same. Thus, in testing the multiperipheral model in this manner, it does not matter whether an experiment is exclusive or inclusive.

As Figure 1 shows, even at the lowest energy considered (23 GeV/c), there is a substantial difference between the predictions of the two models. For this reason, we compare the predictions of the two models with experimentally measured distributions for the reaction $pp \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ at GeV/c.[11] Figure 2 shows various transverse-angle distributions between the final-state particles for this reaction; namely, between the two protons [Fig. 2(a)], between the pions with the largest positive and negative c.m. longitudinal momenta [Fig. 2(b)], between the pions with the smallest longitudinal momentum [Fig. 2(c)], between the protons and the pions with the largest magnitude c.m. longitudinal momentum [Fig. 2(d)], and between the two pions with the second and third largest longitudinal momenta [Fig. 2(e)].

While the distributions involving only pions are slightly better described by the pionization model, these distributions at this energy clearly do not distinguish between the two models. However, the distributions involving the protons, while being adequately described by the pionization model, completely disagree with the predictions of the multiperipheral model. As expected from the qualitative discussion above, the multiperipheral model predicts a large short-range correlation and a smaller long-range correlation, while the pionization model predicts approximately the same for both. The data clearly exhibit the latter behavior.

The models chosen for comparison here are especially simple and represent the extreme limits for the physical processes of pion production. In particular, baryon exchange has been partially neglected in the multiperipheral model,[12] so that each of the two models would have the same number of parameters for comparison with the data. However, inclusion of single-baryon exchange to form a more complete multiperipheral model causes very little change in the results. As an example of the magnitude of this effect, Fig. 2(a) also shows the prediction from a multiperipheral model similar to that of Eq. (2) but including 40% baryon exchange at the nucleon vertices.

Another simplification is the absence of final-state resonances; the effect of resonance production is to cause increased short- as well as long-range correlations.[13] This might help the multiperipheral model agree better with the data in Fig. 2(a), but would cause it to have an even larger disagreement in Fig. 2(d).

The purpose of the present comparison is not to rule out the possible construction of a sufficiently sophisticated multiperipheral model that might describe the data presented in Figure 2; it is merely to illustrate that these data show the exact transverse-angle correlations predicted by unassociated models, and that at present accelerator energies there is no indication of the decrease of long-range correlations required by associated models at high energies.

To summarize, it has been shown that the transverse-angle correlation between final-state leading particles is a sensitive indicator of the nature of secondary particle production in high-energy collisions. Data from pp interactions at 23 GeV/c show no indication of decrease of long-range correlations predicted by associated models. Calculations from a simple multiperipheral model, a particular associated model, show that such deviations should be present at these energies. At higher energies ($\sim$100 GeV/c), the predictions of the two models become very different and, in particular, the multiperipheral model predicts almost no correlation between the leading particles independent of final state multiplicity. Thus, experimental measurements of these transverse angle correlations at high energies could easily distinguish between these two opposing mechanisms for particle production.

Footnotes and References

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†Participating guest.

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1. The Feynman scaling variable, x, is defined as twice the longitudinal momentum divided by the center of mass energy.

2. C.E. DeTar, Phys. Rev. D <u>3</u>, 128 (1971).

3. D.Z. Freedman, C.E. Jones, F.E. Low, and J.E. Young, Phys. Rev. Lett. <u>26</u>, 1197 (1971).

4. However, if the longitudinal-momentum clusters themselves are produced with large transverse momentum relative to the average transverse momentum of a particle within a cluster, then long-range correlations will still be present. This is possible for some associated models (for example, fireball and fragmentation models).

5. All calculations take into account momentum and energy conservation exactly and no approximations were made in performing the phase space integrations necessary for calculating the transverse angle distributions.

6. G.F. Chew and A. Pignotti, Phys. Rev. Lett. <u>20</u>, 1078 (1968), and Phys. Rev. <u>176</u>, 2112 (1968).

7. Chan H.-M., J. Loskiewicz, and W.W.M. Allison, Nuovo Cimento <u>57A</u>, 93 (1968).

8. G. Fox, in <u>High Energy Collisions--Third International Conference</u>, edited by C.N. Yang, J.A. Cole, M. Good, R. Hwa, and J. Lee-Franzini (Gordon and Breach, New York, 1970), p. 367.

9. Although these parameters were specifically adjusted to yield the same transverse-momentum distributions, the two models also produce very similar longitudinal-momentum distributions of both the pions and protons.

10. In calculating $d\sigma/d\varphi$ for this model, we have assumed only M=0 Toller quantum-number exchange (see Ref. 3).

11. The six-pronged events resulting from a proton exposure in the Brookhaven National Laboratory 80-in. H_2 bubble chamber were fitted by the reaction $pp \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ in the beam momentum range 18-28 GeV/c, yielding 970 examples of this reaction. For a detailed description of the experiment see D.B. Smith, Ph.D. thesis, UCRL Report No. UCRL-20632, 1971 (unpublished).

12. The principal effect of baryon exchange is to increase the average transverse momentum of the protons relative to the pions. This is taken into account in the present analysis by adjusting the $\beta_N^2(t)=e^{bt}$ to reproduce the experimental transverse-momentum distributions for the protons.

13. The increase in short-range correlations is a result of clustering of particles due to resonance formation, and the increase in long-range correlations is caused by the effective decrease of the final-state multiplicity.

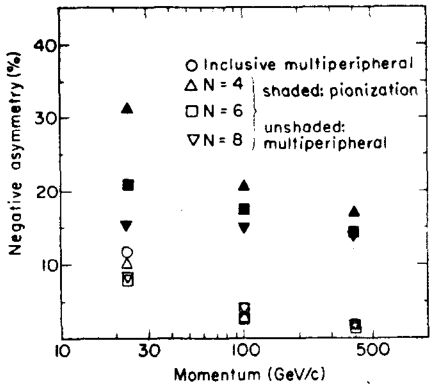

FIG. 1. Backward-forward asymmetry in transverse-angle distributions for final-state nucleons in pp interactions as predicted by pionization and multiperpheral models, for several beam momenta.

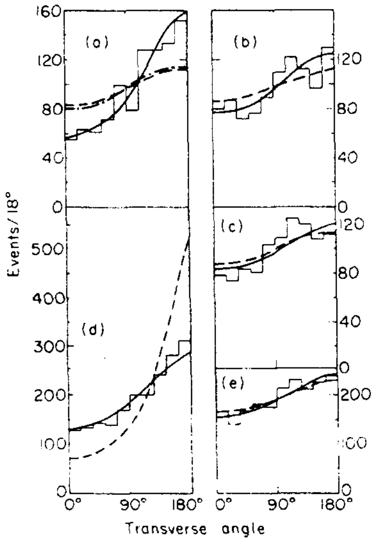

FIG. 2. Experimental transverse-angle distributions between various final-state particles for $pp \to pp\pi^+\pi^+\pi^-\pi^-$ at 23 GeV/c. The dashed lines are the predictions of a multiperipheral model while the solid ones are the predictions of a pionization model; the dot-dashed line is the prediction of a multiperipheral model with baryon exchange (see text).