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AZIMUTHAL CORRELATIONS AND INDEPENDENT
CLUSTER EMISSION MODEL

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ABSTRACT

Azimuthal correlations at NAL and ISR energies are studied in the independent cluster emission model and qualitative agreement with the dependence of these correlations on the collision energy, the transverse momentum and the charge combinations of the pion pair are found.

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The independent cluster model ^{1),2)} so far was applied to inclusive single particle distributions ³⁾, multiplicity distributions ⁴⁾, inclusive and semi-inclusive two-particle rapidity correlations ^{5),6)}. Here we apply this model to the two-particle correlations in the azimuthal angle.

Studies at low energy ⁷⁾⁻¹⁵⁾ have revealed that azimuthal correlations agree rather well with those expected from transverse momentum conservation in a statistical or uncorrelated jet-like picture. Most of these correlation data seem to be independent of the rapidity difference of the two particles considered and therefore appear to contradict the short-range hypothesis and models - like the multiperipheral model - having this property. Azimuthal correlations in the multiperipheral model have been studied in Refs. 16),17). So far, azimuthal correlations at Serpukhov, NAL and ISR energies were not investigated in great detail. Data on some particular aspects have been given in Refs. 18)-20).

Azimuthal correlations were studied by different groups in different forms. We here give our definition. We find it sufficient to study the dependence of the two-particle distribution in $\cos\phi$

$$\cos\phi = \frac{\vec{p}_{1\perp} \cdot \vec{p}_{2\perp}}{|\vec{p}_{1\perp}| |\vec{p}_{2\perp}|}, \quad 0 \leq \phi \leq 2\pi \quad (1)$$

and believe it is of no advantage to study the ϕ dependence of the correlation functions

$$R^{(2)}(p_1, p_2, s) = \frac{\frac{1}{\sigma} \frac{d\sigma}{dp_1 dp_2}}{\frac{1}{\sigma^2} \frac{d\sigma}{dp_1} \frac{d\sigma}{dp_2}} - 1 \quad (2)$$

If no simultaneous rapidity and/or transverse momentum distributions or transverse momentum cuts are considered, the most obvious inclusive ϕ distribution is

$$\rho^{\text{incl.}}(\phi, s) = \frac{2\pi}{\langle n(n-1) \rangle} \iint dy_1 dy_2 d^2\vec{p}_{1\perp} d^2\vec{p}_{2\perp} \Psi^{(2)}(y_1, y_2, \vec{p}_{1\perp}, \vec{p}_{2\perp}, \phi, s) \quad (3)$$

where $\Psi^{(2)}$ is the inclusive two-particle distribution. If there is no correlation, $\rho(\phi, s)$ is equal to 1 and independent of ϕ . Approximately $\rho(\phi, s)$ has the form

$$\rho(\phi, s) \approx 1 - A(s) \cos\phi \quad (4)$$

and one might use the parameter $A(s)$ to describe the strength of the correlation. Another possibility to characterize the ϕ correlation by one single parameter provides the asymmetry parameter

$$B(s) = \frac{\int_{\pi/2}^{\pi} \varrho(\phi, s) d\phi - \int_0^{\pi/2} \varrho(\phi, s) d\phi}{\int_0^{\pi} \varrho(\phi, s) d\phi} \quad (5)$$

Energy and momentum conservation leads to non-vanishing kinematic correlations in ϕ . To estimate this part of azimuthal correlations, it is important to take the observed exponential cut-off of transverse momentum distributions into account.

More interesting are semi-inclusive or inclusive joint rapidity and ϕ distributions. We define the latter in the inclusive case as follows

$$\varrho^{incl.}(y_1, y_2, \phi, s) = \frac{2\pi \iint d^2 p_{\perp 1} d^2 p_{\perp 2} \Psi^{(2)}(y_1, y_2, \vec{p}_{\perp 1}, \vec{p}_{\perp 2}, \phi, s)}{\iint d^2 p_{\perp 1} d^2 p_{\perp 2} d\phi \Psi^{(2)}(y_1, y_2, \vec{p}_{\perp 1}, \vec{p}_{\perp 2}, \phi, s)} \quad (6)$$

The approximate form for non-vanishing ϕ correlation is

$$\varrho^{incl.}(y_1, y_2, \phi, s) \approx 1 - A(y_1, y_2, s) \cos \phi \quad (7)$$

and the function $A(y_1, y_2, s)$ might be used to describe the correlation. Besides the rapidity dependence of $\varrho^{incl.}$ also its transverse momentum dependence is of interest. Distribution functions including the transverse momentum dependence can be defined similarly to Eq. (6).

Data on inclusive anisotropy parameter (5) and the inclusive distribution (3) have been published for $\pi^+\pi^+$, $\pi^-\pi^-$, $\pi^+\pi^-$ in 40 GeV/c π -p interactions in Ref. 18) and in 102 GeV/c pp interactions in Ref. 19). The latter experiment also gives data for pairs of particles in the rapidity intervals $\Delta y < 1$ and $\Delta y > 2$. In Table 1, we collect the anisotropy parameters according to these two experiments.

The characteristic features of these data are :

- i) the $\emptyset$ anisotropy of pion pairs of like charge is only about half as big as for pions of unlike charge;
- ii) at 102 GeV/c, the $\emptyset$ anisotropy for small rapidity separation of the two pions is larger than for large Δy . This indicates the presence of a short-range component in the $\emptyset$ correlations, but an important long-range correlation is also present.

The CERN-Hamburg-Vienna ISR collaboration ²⁰⁾ has measured differently defined inclusive azimuthal correlations

$$R^{(2)}(y_1, y_2, \phi) = \frac{\Psi^{(2)}(y_1, y_2, \phi)}{\Psi^{(1)}(y_1) \Psi^{(1)}(y_2)} - 1 \quad (8)$$

and

$$R^{(2)}(y_1, y_2, p_{\perp 1}, \phi) = \frac{\Psi^{(2)}(y_1, y_2, p_{\perp 1}, \phi)}{\Psi^{(1)}(y_1) \Psi^{(1)}(y_2)} - 1 \quad (9)$$

and the correlation function was presented by giving the parameter b of

$$R^{(2)}(\phi) = a + b \cos \phi \quad (10)$$

where $a \equiv R^{(2)}(y_1, y_2)$ is presented in the same paper. For (8), it is $b = b(y_1, y_2, s)$ and for (9) it is $b = b(y_1, y_2, p_{\perp 1}, s)$. From the published data we obtain $A(y_1, y_2, s)$ of Eq. (7) as

$$A(y_1, y_2, s) = - \frac{b}{1+a} \quad (11)$$

The CERN-Hamburg-Vienna collaboration finds negative b values which increase in absolute value with increasing $p_{\perp 1}$. In the Figure we plot the transverse momentum dependence of our parameter $A(y_1, y_2, s)$ obtained from Eq. (11) from the curves published in Ref. 20). As function of Δy the $\emptyset$ correlation data of all rapidity separations is of about equal strength indicating long-range correlations at least for $p_{\perp 1} > 0$. The badly understood feature of the data is the absence of a short-range effect; this is in contradiction with the data at 102 GeV/c ¹⁹⁾.

Azimuthal correlations in an uncorrelated jet model with transverse momentum cut-off, as observed in single particle distributions, were calculated in Refs. 7), 10) and 21) for fixed multiplicity as

$$\frac{d\sigma_m}{d\phi} = \rho^{(m)}(y_1, y_2, \phi) = 1 - \frac{\pi}{2} \frac{1}{n-1} \cos \phi \equiv \rho^{(m)}(\phi). \quad (12)$$

The corresponding asymmetry coefficient $B(s)$ defined in Eq. (5) is

$$B(s) = \frac{1}{n-1}. \quad (13)$$

We stress that the ϕ distribution is independent of the relative rapidities of the particles considered. The same result, (12), was obtained for the isotropic decay of one single cluster in Refs. 22) and 23) according to the statistical bootstrap model from kinematics only ²²⁾ or by considering the integral equation for the fireball decay .

The azimuthal correlations in the uncorrelated jet model as well as in the cluster decay depend strongly on the transverse momenta of the observed particles ^{10), 23)}

$$\rho^{(m)}(p_{\perp 1}, p_{\perp 2}, \phi) = 1 - \frac{\pi}{2} \frac{p_{\perp 1} p_{\perp 2}}{\langle p_{\perp} \rangle^2 (n-1)} \cos \phi. \quad (14)$$

Semi-inclusive two-particle distribution functions of the rapidity of the two-particles were expressed in Ref. 5) in the form

$$\begin{aligned} \mathcal{T}_2^{(m)}(y_1, y_2, s) = n(n-1) & \left[\sum_{m=1}^{m_{\max}} w_m(s) \frac{1}{m} \sum_{n_1=2}^{n-2(m-1)} Q_2^{av,m}(n_1, y_1, y_2) \right. \\ & \cdot P_{m-1}^{av,m}(n-n_1) + \sum_{m=2}^{m_{\max}} w_m(s) \frac{m-1}{m} \sum_{n_1=2}^{n-2(m-1)} Q_1^{av,m}(n_1, y_1) \cdot \\ & \left. \sum_{n_2=2}^{n-n_1-2(m-2)} Q_1^{av,m}(n_2, y_2) P_{m-2}^{av,m}(n-n_1-n_2) \right]. \end{aligned} \quad (15)$$

n is the number of all charged and neutral particles in the collision. $Q_1^{av,m}(n, y)$ and $Q_2^{av,m}(n, y_1, y_2)$ are single and two-particle rapidity distributions resulting from the decay of one average fireball, m is the number of

clusters and $w_m(s)$ is their multiplicity distribution. The functions $P_l^{av,m}(k)$ are the multiplicity distributions of k particles emerging from l out of m average clusters, see Ref. 5). The first term in Eq. (15) refers to emission of both particles from the same cluster, in the second term the two particles emerge from two different clusters.

For two particles coming from the same cluster which decays into n_1 particles we use Eq. (12) which was obtained in Ref. 23). The joint rapidity and ϕ distribution according to this first term is

$$\left. \varrho^{(n)}(y_1, y_2, \phi) \right|_{1F} \approx \sum_{m=1}^{m_{max}} w_m(s) \frac{1}{m} \sum_{n_1=2}^{n-2(m-1)} Q_2^{av,m}(n, y_1, y_2) \cdot P_m^{av,m}(n-n_1) \left(1 - \frac{\pi}{2} \frac{1}{(n_1-1)} \cos \phi \right). \quad (16)$$

In the independent cluster emission model, clusters are produced uncorrelated but this implies that clusters have kinematical ϕ correlations due to conservation of the transverse momenta of clusters. Therefore also particles resulting from the decay of two different clusters will be correlated in ϕ .

In order to calculate the ϕ distribution of this term, we should take into account the ϕ dependence and the transverse momentum distribution of the production as well as the decay of the clusters. Since we do not want to introduce a special model, we describe the ϕ anisotropy of two particles from two different fireballs by the anisotropy parameter $B_{2F}^{(n)}(s)$ similar to $B(s)$ defined in Eq. (5). $B_{2F}(s)$ will be estimated below. The joint rapidity and ϕ distribution of the two-cluster contribution is

$$\left. \varrho^{(n)}(y_1, y_2, \phi) \right|_{2F} \approx \sum_{m=2}^{m_{max}} w_m(s) \frac{m-1}{m} \sum_{n_1=2}^{n-2(m-1)} Q_1^{av,m}(n_1, y_1) \cdot \sum_{n_2=2}^{n-n_1-2(m-2)} Q_1^{av,m}(n_2, y_2) P_{m-2}^{av,m}(n-n_1-n_2) \left(1 - \frac{\pi}{2} B_{2F}^{(n)}(s) \cos \phi \right) \quad (17)$$

As discussed in Ref. 5) the n and m dependence of the functions $Q_1^{av,m}(n, y, s)$ and $Q_2^{av,m}(n, y_1, y_2, s)$ can be neglected. We introduce the functions

$$\begin{aligned}\tilde{Q}_1^{av}(y, s) &= Q_1^{av, m}(n, y, s) / P_1^{av, m}(n) \\ \tilde{Q}_2^{av}(y_1, y_2, s) &= Q_2^{av, m}(n, y_1, y_2, s) / P_1^{av, m}(n).\end{aligned}\quad (18)$$

The single and two-cluster contribution together give the semi-inclusive $\emptyset$ correlation function

$$\begin{aligned}\varphi^{(n)}(y_1, y_2, \phi) &= \left[\tilde{Q}_2^{av}(y_1, y_2, s) \langle \frac{1}{m} \rangle \left(1 - \frac{\pi}{2} \langle \frac{1}{n_1-1} \rangle \cos \phi \right) \right. \\ &\quad \left. + \tilde{Q}_1^{av}(y_1, s) \tilde{Q}_1^{av}(y_2, s) \left(1 - \langle \frac{1}{m} \rangle \right) \left(1 - \frac{\pi}{2} B_{2F}^{(n)}(s) \cos \phi \right) \right] \\ &\quad \left[\tilde{Q}_2^{av}(y_1, y_2, s) \langle \frac{1}{m} \rangle + \tilde{Q}_1^{av}(y_1, s) \tilde{Q}_1^{av}(y_2, s) \left(1 - \langle \frac{1}{m} \rangle \right) \right]^{-1}.\end{aligned}\quad (19)$$

We find the inclusive $\emptyset$ distribution $\rho^{\text{incl}}(y_1, y_2, \emptyset)$ in the form of Eq. (19) where, however, we have to replace $B_{2F}^{(n)}(s)$ by its value averaged over all n , $B_{2F}(s)$. This form predicts stronger $\emptyset$ correlations for small rapidity differences $\Delta y = |y_1 - y_2|$ in agreement with the experimental results at 102 GeV/c ¹⁹⁾.

The average value of $1/(n_1-1)$ in Eq. (19), $\langle 1/(n_1-1) \rangle$, can be estimated from the charged multiplicity distribution σ_n^{1F} v. n of average fireballs obtained in Ref. 5). With

$$B_{1F}(s) = \langle \frac{1}{n_1-1} \rangle = \frac{\sum_{m=2}^{m_{\max}} \frac{1}{\sigma_{\text{tot}} - 1} \sigma_m^{1F} w_n^{ij}}{\sum \sigma_m^{1F} w_n^{ij}} \quad (20)$$

we find for different charge combinations

$$B_{1F}(s) = \langle \frac{1}{n_1-1} \rangle = \begin{cases} 0.195 & \text{for } \pi^+ \pi^- & (ij = +-) \\ 0.131 & \text{for } \pi^+ \pi^+ & (ij = ++) \\ 0.131 & \text{for } \pi^- \pi^- & (ij = --) \end{cases} \quad (21)$$

It is

$$\begin{aligned} W_n^{+-} &= \frac{n}{2} \frac{n}{2} \\ W_n^{++} &= W_n^{--} = \begin{cases} 0 & \text{for } n < 4 \\ \frac{n}{2} \left(\frac{n}{2} - 1 \right) & \text{for } n \geq 4 \end{cases} \end{aligned} \quad (22)$$

and we approximate the multiplicity in the decay of one cluster

$$n^{1F} = n_{\text{tot}}^{1F} = \frac{3}{2} n_{\text{ch}}^{1F} . \quad (23)$$

The asymmetry parameter according to statistical production in pp collisions can be estimated by an expression equivalent to (20) from the charged multiplicity distribution. In this case the weights w_n^{ij} are approximately

$$\begin{aligned} W_n^{+-} &= \begin{cases} 0 & \text{for } n = 2 \\ \frac{n-2}{2} \left(\frac{n-2}{2} + 0.5 \right) & \text{for } n \geq 3 \end{cases} \\ W_n^{--} &= \begin{cases} 0 & \text{for } n \leq 4 \\ \frac{n-2}{2} \left(\frac{n-2}{2} - 1 \right) & \text{for } n \geq 5 \end{cases} \\ W_n^{++} &= \begin{cases} 0 & \text{for } n = 2 \\ \left(\frac{n-2}{2} + 0.5 \right) \left(\frac{n-2}{2} - 0.5 \right) & \text{for } n \geq 3 \end{cases} . \end{aligned} \quad (24)$$

Using experimental data for the charged multiplicity distribution at 102 GeV/c²⁴⁾ and the KNO fit²⁵⁾ at $\sqrt{s}=30$ GeV, we obtain $B^{\text{incl}}(s)$ as given in Table 2. With these values, we estimate the asymmetry $B_{2F}(s)$. We assume the asymmetry Eq. (5) integrated over all rapidities which can be calculated from Eq. (19) to behave similarly to the statistical asymmetry $B^{\text{incl}}(s)$ given in Table 2

$$\left\langle \frac{1}{n-1} \right\rangle^{ij} = \left\langle \frac{1}{n} \right\rangle \left\langle \frac{1}{n-1} \right\rangle + \left(1 - \left\langle \frac{1}{n} \right\rangle \right) B_{2F}(s) . \quad (25)$$

At 102 GeV/c we have about three and at $\sqrt{s}=30$ GeV about four fireballs. Using Eq. (21) and $B^{\text{incl}}(s)$ given in Table 2, we obtain from Eq. (25) for $B_{2F}(s)$ the values listed also in Table 2. This $B_{2F}(s)$ is the minimal asymmetry which is demanded by kinematics. Various dynamical schemes might lead to a larger $B_{2F}(s)$. With these estimated values together with numerically obtained

values for $\tilde{Q}_1^{\text{av}}(y,s)$ and $\tilde{Q}_2^{\text{av}}(y_1,y_2,s)$ ⁵⁾ which are also collected in Table 2, we calculate at 102 GeV/c and at $\sqrt{s}=30$ GeV the asymmetry parameters presented in Table 3. The values at 102 GeV/c can be directly compared with the data given in Table 1. We compare the calculated $B(y_1=0, y_2=0)$ with the experimental $B(\Delta y < 1)$ and the calculated $B(y_1=0, y_2=2.5)$ with the experimental $B(\Delta y > 2)$. The numerical values for $\pi^+\pi^-$ correlations agree rather well, for $\pi^+\pi^+$ and $\pi^-\pi^-$ we obtain smaller theoretical asymmetry parameters but not small enough to agree with data. At $\sqrt{s}=30$ GeV the asymmetry parameter calculated can be compared with the transverse momentum dependence of the azimuthal correlations as given in the Figure according to the data of Ref. 20). Using Eq. (14), the dependence of the parameter $A(p_{1\perp}, y_{\text{ch}}=0, y_{\text{v}}=2.5)$ is obtained as

$$A(p_{1\perp}, y_{\text{ch}}=0, y_{\text{v}}=2.5) = \frac{\pi}{2} B(y_1=0, y_2=2.5, s) \frac{p_{1\perp}}{\langle p_{1\perp} \rangle} \quad (26)$$

Using $B(y_1, y_2, s)$ of Table 3, this curve has been plotted in the Figure together with the data and we find reasonable agreement.

We conclude that the independent cluster model allows to understand the essential features of the azimuthal correlations, especially :

- i) the rapidity dependence, where a short and a long-range term are found in agreement with data at 102 GeV/c, but in disagreement with the ISR data ²⁰⁾;
- ii) the transverse momentum dependence;
- iii) the dependence of the various charged pairs of the two pions. In the model we find smaller ϕ correlations for like pion pairs as found experimentally, but the difference to the unlike pions is not large enough. This could indicate the well-known Goldhaber effect due to Bose statistics of identical particles;
- iv) the s dependence of transverse momentum correlations of the rather limited data seems to be well reproduced by the model.

We remark that it is worth while to measure azimuthal correlations in more detail, especially in channels with fixed multiplicity, where the model could be tested better than with inclusive data.

Furthermore, we stress the importance of remeasuring the rapidity dependence of the ϕ asymmetry in order to establish the short-range effect conclusively.

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Channel	40 GeV/c π -p	102 GeV/c pp	102 GeV/c pp, $\Delta y < 1$	102 GeV/c pp, $\Delta y > 2$
$\pi^+\pi^-$	0.106 ± 0.003	0.078 ± 0.01	0.098 ± 0.01	0.054 ± 0.01
$\pi^+\pi^+$	0.062 ± 0.006	0.040 ± 0.01	0.032 ± 0.01	0.028 ± 0.01
$\pi^-\pi^-$	0.062 ± 0.006	-	-	-

Table 1 : Asymmetry parameters $B(s)$ defined in Eq. (13) measured in Refs. 18) and 19). The 102 GeV/c values have been computed from published data ¹⁹⁾.

$\sqrt{s}$	ij	B_{incl}^{ij}	$\tilde{Q}_2^{\text{av}}(y_1=0, y_2=0)$	$\tilde{Q}_2^{\text{av}}(y_1=0, y_2=2.5)$	$\tilde{Q}_1^{\text{av}}(y_1=0)$	$\tilde{Q}_1^{\text{av}}(y_1=2.5)$	B_{2F}
13.76	+	-	0.083	0.105	0.0058	0.248	0.076
	+	+	0.080				
	-	-	0.073				
30	+	-	0.058	0.095	0.0052	0.190	0.067
	+	+	0.057				
	-	-	0.053				
							0.015

Table 2 : Numerical values of quantities used to compute $B_{2F}(s)$, the asymmetry parameter in case that both particles emerge from two different clusters.

	$\sqrt{s}=30$ $y_1=0, y_2=0$	$\sqrt{s}=30$ $y_1=0, y_2=2.5$	100 GeV/c pp $y_1=0, y_2=0$	100 GeV/c pp $y_1=0, y_2=2.5$
$\pi^+ \pi^-$			0.103	0.049
$\pi^+ \pi^+$			0.075	0.04
$\pi^- \pi^-$			0.075	0.04
ch 0	0.1	0.036		

Table 3 : Theoretical values of the asymmetry parameters $B(y_1, y_2, s)$ computed from Eq. (21).

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FIGURE CAPTION

Transverse momentum dependence of the azimuthal correlation parameter $A(y_1, y_2, s)$ defined in Eq. (11) according to the CERN-Hamburg-Vienna collaboration ²⁰⁾ at $\sqrt{s} = 30$ GeV. The curve has been computed from Eq. (14).

FIG. 1