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n-Particle Transverse Correlation and Collectivity for 1.2 *A* GeV Ar + KCl Collisions

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An *n*-particle transverse correlation function for analysis collective flow is proposed, which extends the study of *n*-particle azimuthal correlations and the estimation of collectivity to include the effects of both magnitude and angle for the *n*-particle transverse momentum vectors. This method is more sensitive to the collectivity of collective flow than the method based on multi-particle azimuthal correlations. Using the new method, *n*-particle transverse correlations are analyzed for collisions of 1.2 *A* GeV Ar + KCl in the Bevalac streamer chamber, and the results have been compared with a Monte Carlo simulation, which show that the collectivity for this experiment is between 85% and 95%.

1. INTRODUCTION

In 1974 Scheid et al. [1] predicted the existence of collective flow and suggested to obtain information about the nuclear equation of state through the study of collective flow. Since then, sphericity analysis [2], transverse momentum analysis [3], the method of Beckmann et al. [4],

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azimuthal distribution function analysis [5] and particle pair correlation function analysis [6] have been proposed to study collective flow. So far, the large amount of experimental results not only proves the existence of the collective flow, but also increase the understanding of the nuclear equation of state and the reaction mechanism of relativistic heavy ion collisions by comparing it with model predictions [7]. In the methods listed above, the flow parameters reflect different aspects of the magnitude of collective flow. Recently, Jiang et al. [8] generalized the particle pair correlation function analysis to study n-particle azimuthal correlations for 0.4 A GeV Ar + Pb collisions in the Bevalac streamer chamber and to infer the collectivity, a characteristic of collective flow never revealed before by the traditional flow analyses. But the information of transverse momentum magnitude has not been considered in their study of n-particle azimuthal correlations and the collectivity estimation. The goal of this paper is to generalize both the study of n-particle azimuthal correlations and the estimation of the collectivity to include the information of the magnitudes and the azimuthal angles for all of the n particle transverse momentum vectors. In Sec. 2, we introduce an n-particle transverse correlation function method for studying collective flow, in which the variable of the correlation function is related to the magnitudes and the azimuthal angles of the n particle transverse momenta. In Sec. 3, a brief introduction of experimental events for 1.2 A GeV Ar + KCl collisions at the Bevalac streamer chamber is given, and the steps to generate Monte Carlo events are sketched. In Sec. 4, n-particle transverse correlations for the experimental data sample are analyzed and the collectivity is inferred by comparing the experimental results with the Monte Carlo simulations. Finally, in Sec. 5, conclusions are given.

2. COLLECTIVITY AND n-PARTICLE TRANSVERSE CORRELATION

The relativistic nucleus-nucleus central collisions produces a fireball at high temperature and high density. Suppose the number of particles emitted forward in the center-of-mass system of the fireball is M, and the number of particles participating in the collective directed motion is M_1, the collectivity α is defined as

$$\alpha = (M_1/M) \cdot 100\% \ , \tag{1}$$

Using information of transverse momentum vector, we use the following variable W,

$$W = \left|\sum_{i=1}^{M} p_\perp(i)\right| / \sum_{i=1}^{M} |p_\perp(i)| , \tag{2}$$

where $p_\perp(i)$ is the transverse momentum vector of the i-th particle. W is a measure of the strength of collective flow, but the information in W about the collectivity has been concealed due to the summation over transverse momenta, so the collectivity cannot be estimated with the method introduced in [4] and [9].

Using the information of azimuthal angles, [8] inferred the collectivity by studying n-particle azimuthal correlations. The multi-particle variable chosen in [8] is

$$\Psi_n = \left(\prod^{k} \Delta\phi\right)^{1/k}, \qquad k = n(n-1)/2, \tag{3}$$

where the product runs over all K azimuthal separations formed from the n particles.

In this paper, in order to generalize the study of n-particle azimuthal correlations and the estimation of collectivity to include both the momentum magnitudes and the azimuthal angles, we study n-particle transverse correlations in M particles as follows. First, randomly select n-particle subevent from a event of multiplicity M, then calculate the following variable for each subevent

$$V_n = |\sum_{i=1}^{n} p_\perp (i)| / \sum_{i=1}^{n} |p_\perp (i)| \, , \tag{4}$$

where $p_\perp (i)$ stands for the transverse momentum vector of i-th particle of the subevent. The variable V_n is related to the magnitudes and the azimuthal angles of the transverse momentum of n particles, and reflects the extent to which n particles preferentially emit in both the number of particles and the magnitudes of transverse momenta. Then, the distribution function $D(V_n)$ of subevents selected from collision events and the distribution function $B(V_n)$ of subevents selected from background events are calculated. Based on the definition of the correlation function in pion interferometry, the following n-particle transverse correlation function is defined:

$$F(V_n) = D(V_n)/B(V_n), \tag{5}$$

For each experimental event, randomly choosing the azimuthal angle for each of the M particles between 0 to 2π while maintaining the polar angle and the magnitude of the momentum vector unchanged, we obtain a corresponding background event [4]. Because there is no transverse correlations in the background event, we can extract information about n-particle transverse correlations through studying $F(V_n)$.

The number of n-particle subevents constructed from each event of multiplicity M is $\Xi = M!/(M-n)!\,n!$. Because the experimental sample contains a wide range of multiplicity, events with higher M completely swamp those with lower M at large n when all the subevents have equal weight. To compensate for this, all the contributions are weighted by M/Ξ, thus ensuring that the contribution of each event to the final result is proportional to the multiplicity M of the event [8].

3. EXPERIMENTAL EVENTS AND MONTE CARLO EVENTS BASED ON CASCADE MODEL

The experimental data sample for 1.2 A GeV Ar + KCl collisions is from the Bevalac streamer chamber, which contains 571 events with charged particle multiplicity greater than 30. According to a simple geometrical model, impact parameters for these events are in the range of 0-3.6 fm. The description in more detail can be found in [11] and [12]. To avoid the effect of experimental factors such as particle misidentification, and absorption and energy loss in the target[13], n-particle transverse correlations are studied only for the forward emitted fragments in the center-of-mass system of the fireball ($y_{\rm Lab} > y_{\rm c.m.}$) and with a polar angle cut ($\theta_{\rm Lab} \geq 5°$). The range of multiplicity M' after cuts is [12-19], the average value $\langle M' \rangle$ is 15.

In this paper, the collectivity of the experimental sample is phenomenologically estimated through comparison between the n-particle transverse correlation data for the Monte Carlo simulation and the experimental data. Monte Carlo events are generated by adding the collective motion components produced through the transverse collective flow parametrization introduced in [14], to events generated by Cugnon's cascade model [15]. The steps are as follows.

(1) A cascade sample with statistics twice that of the experimental sample is generated in the impact parameter range of 0-3.6 fm. This model does not explicitly incorporate the effects of the nuclear equation of state.

(2) The polar angle and the rapidity cuts mentioned above are applied to this cascade sample. It has been verified that the distribution of the multiplicity M' after cuts conforms with the experimental data.

(3) For every event of multiplicity M', a component of collective directed motion $f_0 p_i^{\rm flow}$ is added to the projection of transverse momentum on the reaction plane [8] for each fragment, where f_0 is a free parameter that controls the magnitude of the flow, $p_i^{\rm flow}$ is expressed as [14]

$$p_i^{\text{flow}} = A_i B_{ui} |\cos\phi_i| \ , \tag{6}$$

where A_i is the mass number; B is defined as

$$B = \sin^{2/3}(\pi b / b_{\max}) \ , \tag{7}$$

here b is the impact parameter, and $b_{\max} = R_P + R_T$, R_P and R_T are the radii of the projectile and target, respectively; u_i is the center-of-mass rapidity of the fragment in the unit of beam rapidity; ϕ_i is the angle of the transverse momentum vector relative to the reaction plane. Equation (7) phenomenologically describes the dependence of the transverse collective flow on fragment mass, rapidity and azimuthal angle relative to the reaction plane, and the impact parameter. This prescription maintains momentum and energy conservation for each event, and is approximately consistent with the available experimental data [8,14] but is certainly not uniquely constrained by them. Adjusting the parameter f_0 to reproduce the experimental findings for particle-pair correlation function $C(\psi_2)$ or the average in-plane transverse momentum as a function of the rapidity $\langle p_\perp^x(y)\rangle$, f_0 is found to be equal to 310 MeV.

(4) A Monte Carlo sample with collectivity α and the flow parameter f_0 is obtained as follows. Randomly selecting M_1 particles from a event of the multiplicity M' obtained in the step 2, the component of collective directed motion $f_0 p_i^{\text{flow}}/\alpha$ is added to the projection of the transverse momentum on the reaction plane for each one of the M' particles (following the definition of collectivity, $M_1 = \alpha M'$). Adding the collective directed motion component in this way, a constant value of f_0 results in continued agreement of $C(\psi_2)$ and $\langle p_\perp^x(y)\rangle$. If the transverse correlation function $F(V_n)$ for the Monte Carlo sample is consistent with the experimental data sample for a given input value of α, then we infer that the input value of α is the collectivity of particles in the final state for this experiment.

4. ANALYSIS OF EXPERIMENTAL EVENTS AND MONTE CARLO SIMULATION EVENTS

Figure 1(a) and (b) show the variation of $F(V_n)$ with V_n for $n = 9$ and $n = 10$, respectively. The solid circle represents the experimental data. The experimental data are not always equal to 1, indicating the existence of transverse correlations among the particles in the final state. Furthermore, $F(V_n)$ is a monotonically increasing function when $n \leq 9$, and the higher the order n is, the greater the value of $F(V_n)$ near $V_n = 1$; in contrast, the slope of $F(V_{10})$ turns negative near $V_{10} = 1$.

Before adding the collective flow component, $F(V_n) \approx 1$ for the cascade sample. This shows that the contribution of any flow produced by cascade model to the variation of $F(V_n)$ with V_n can be

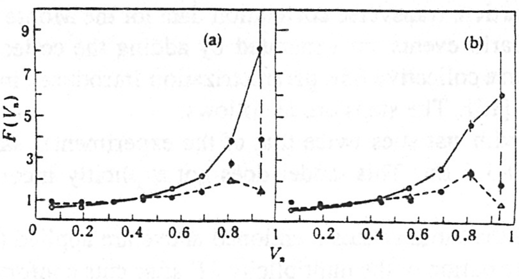

Fig. 1

The transverse correlation function $F(V_n)$ for comparison of experimental data (•) Monte Carlo data (o for $\alpha = 95\%$ and Δ for $\alpha = 85\%$). (a) is for $n = 9$; (b) is for $n = 10$.

neglected. Therefore, it can be considered that the characteristic of $F(V_n)$ is only determined by the strength and the collectivity of the phenomenological flow. For a given n, $F(V_n)$ increases with enhanced strength and collectivity of flow. For a sample with a given strength and a specified collectivity, there is a turning point n_0. At $n = n_0$, the slope of $F(V_n)$ changes sign.

Keeping f_0 unchanged, the Monte Carlo results of $F(V_n)$ for different α has been calculated and compared with experimental data. In Fig. 1 the open circle (connected with solid line) and the triangle (connected with dashed line) represent the Monte Carlo data for $\alpha = 95\%$ and $\alpha = 85\%$, respectively. The calculated results show that $n_0 = 9$ when $\alpha = 85\%$; and Fig. 1(b) indicates that $n_0 = 10$ when $\alpha = 95\%$. The turning point n_0, where $F(V_n)$ changes its slope is sensitive to the collectivity of the flow. From Fig. 1 we conclude that when α varies in a range of 85% and 95%, the Monte Carlo results of n-particle transverse correlations are consistent with the experimental data within the current accuracy.

On the other hand, using the method introduced in [8], we compare n-particle azimuthal correlation function $C(\psi_n)$ of Monte Carlo simulation with that of experimental data, which shows the collectivity is not less than 85% within the range of estimated error.

5. CONCLUSIONS

An n-particle transverse correlation function analysis for the study of the collective flow is proposed. The variable used in the method is similar to that introduced by Beckmann et al., which is related to the magnitude and azimuthal angle of the transverse momentum vector for the n particles so that it contains not only the information of the azimuthal angles but also that of the momentum magnitudes for the n particles. We randomly divide each event into a group of the n-particle sub-events to study particle transverse correlation for different order n. Then the information of the collectivity can be revealed, which is concealed by the summation over the transverse momentum in the variable. The method proposed in this paper generalize the study of the n particle azimuthal correlation and the estimation of the collectivity to include the information of both magnitude and azimuthal angle for the transverse momentum.

When n is lower, the correlation function $F(V_n)$ of the n-particle sub-events is a monotonically increasing function. As n increases, there is a turning point n_0 making $F(V_n)$ decreasing near $V_n \approx 1$. Monte Carlo simulation indicates that this turning point is sensitive to the collectivity of the collective flow. n-Particle transverse correlations for collisions of 1.2 A GeV Ar + KCl at the streamer chamber have been analyzed. Comparing the experimental results with the Monte Carlo simulation, the collectivity is estimated to be in the range 85%-95%, which is more decisive than the result (85%-100%) obtained from multi-particle azimuthal correlation function analysis. Our analysis includes not only the information of the azimuthal angle but also that of the magnitude of the transverse momentum, and provides more constraint to determine the collectivity with the same data statistics.

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