Peripheral tube model for centrality dependence of di-hadron correlations

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ABSTRACT

The data of di-hadron azimuthal correlations at different centralities for Au+Au collisions at 200 A GeV were presented by the PHENIX Collaboration. It was observed that the away-side correlation evolves from double- to single-peak structure when the centrality decreases. In this work, we show, in terms of the peripheral tube model, that the observed features naturally appear due to an interplay between the flow due to the peripheral tube and the background elliptic flow. A key feature of the present approach is that the event-by-event fluctuating initial conditions are represented by the randomly distributed peripheral tubes. We also carry out numerical simulations by using the hydrodynamical code NeXSPheRIO, and calculate the correlations by the ZYAM method employed by PHENIX Collaboration. It is shown that our results are in reasonable agreement with the data.

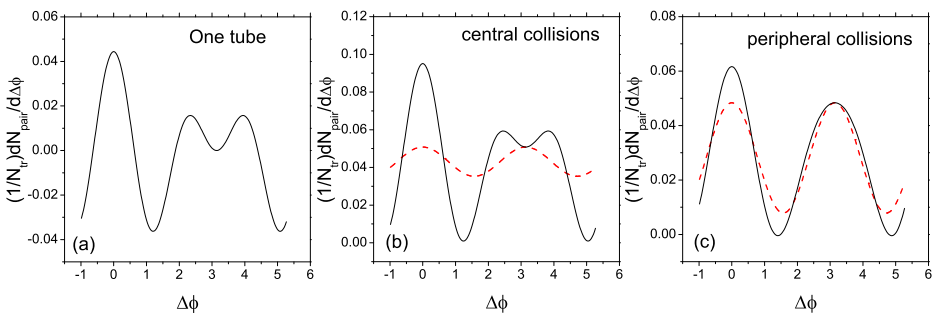
1 Introduction

1.1 Data on di-hadron correlations

The di-hadron correlations in ultra-relativistic heavy-ion collisions are fundamental observables reflecting the properties of the underlying particle production mechanisms. The observations of enhancement in correlations at intermediate and low p_T strongly indicate the hydrodynamics/transport nature of such phenomena [1, 2]. The structure on the near side of the trigger particle is referred to as "ridge". It features a narrow peak in $\Delta\phi$, located around zero, and a long extension in $\Delta\eta$, and therefore is related to a long-range correlation in pseudo-rapidity. The away-side correlation broadens, in $\Delta\phi$, from peripheral to central collisions, and it exhibits double peak for certain centralities and particle-p_T ranges. The latter is usually called "shoulders". Data from the PHENIX collaboration indicated a centrality dependence of the correlation [3] that the away-side correlation evolves from double- to single-peak structure when the centrality decreases.
The current understanding is that particle correlation can be mostly interpreted by collective flow, or to be specific, the flow dynamics observed in terms of anisotropic parameters, v_n. The latter is closely related to the corresponding ϵ_n, the energy density anisotropy parameters of the initial conditions (IC) [2]. Therefore, it is believed in general that the study of v_n will give a clue to determine the initial energy distribution. In this sense, the di-hadron correlations observed in Ref.[3] are generally attributed to the triangular flow, created by the fluctuations in the IC. However, as pointed out by some authors [4, 5] that the correspondence between v_n and ϵ_n is not one-to-one. Moreover, to understand the mechanism of how these event-by-event fluctuations are created, it is essential to clarify the initial and subsequent dynamics of relativistic heavy ion collisions. In this context, the peripheral tube model [5, 6] provides a very straightforward and reasonable mechanism for the generation of the triangular flow and di-hadron correlations.

1.2 The peripheral tube model

In a previous work [7], the peripheral tube model was employed to discuss the trigger-angle dependence of the di-hadron correlation in mid-central collisions (20%-60% centrality). This approach seeks to provide an intuitive interpretation for the observed characteristics of the two particle correlations, rather than to replace the realistic event by event hydrodynamical calculations. A key component of the model is that the background collective flow is deflected by a peripheral tube (or "hot spot") emerging from the fluctuating initial conditions, and subsequently contributes to the resulting two-particle correlation. In this context, the "deflected flow" from the tube is not allineated to the event plane but associated with the azimuthal angle of random initial fluctuations. In fact, this distinct feature offers a more straightforward description of the observed trigger-angle dependence of the di-hadron correlation. By a simplified analytical approach, the resultant correlations were understood as due to the interplay between two components, namely, the elliptic flow caused by the initial almond-shaped deformation of the whole system and the flow produced by tubelike fluctuations. Specifically, the latter is already present in the central collisions, with the characteristic 3-peak shape of correlation in $\Delta\phi$ [6]. The contribution of the former is trigger-angle dependent: it is back-to-back (peaks at $\Delta\phi = 0, \pi$) in the case of in-plane triggers ($\phi_s = 0$) and it is shifted by $\pi/2$ (peaks at $\Delta\phi = -\pi/2, \pi/2$) in the case of out-of-plane triggers ($\phi_s = \pi/2$). Therefore, in the out-of-plane direction, the "valley" at $\Delta\phi = \pi$ helps to form the observed double-peak structure; while at the in-plane direction, the peak at $\Delta\phi = \pi$ strengthens the correlation on away side, resulting in a single peak.
The present work follows this line of thought, we extend the above model to study the centrality dependence of the di-hadron correlation. In order to discuss the average correlation at different centrality windows, one integrates the results obtained in [7] over the azimuthal angle of the trigger particle. The centrality dependence comes out naturally from that of the background elliptic flow, whose magnitude increases from central to peripheral collisions. As a result, when one goes from peripheral to central collisions, the away-side correlation is expected to evolve from single- to double-peak structure and meanwhile, the magnitude of the correlation increases. This was exactly observed in the measurements carried out by PHENIX Collaboration. In what follows, we first show that the main feature of the two particle correlations can be qualitatively reproduced by using the peripheral tube model. The numerical simulations are carried out in section III by employing the hydrodynamical code NeXSPheRIO, and the correlations are evaluated and compared to the data.
The hydrodynamic code SPheRIO[8] employed in this work is base on Smooth Particle Hydrodynamic, an algorithm originally developed in astrophysics and adapted to relativistic heavy ion collisions. It parameterizes the matter flow in terms of discrete Lagrangian coordinates, we call it SPH particles. Those SPH particles are attached to small volumes with some conserved quantities. The hydrodynamic equation is governed by the continuity equations expressing the conservation of energy-momentum, baryon-number, and other conserved charges. In term of SPH degree of freedom, the equation of motion is derived by using the variational principle. Its main advantage is that any complex geometry and violent dynamics such as shock phenomena can be treated without any numerical difficulties, providing that the size of particles is appropriately chosen. We shall neglect in this work any dissipative effects and also assume Cooper-Frye sudden freeze-out take place at constant temperatures. It is noting that there is no free parameter in the present simulation since the few existing ones have been fixed in earlier studies of η and p_T distributions.



The above figures show the resultant di-hadron correlations calculated by the peripheral tube model using cumulant and ZYAM method. The main feature of the observed data is reproduced by the toy model proposed in the next section. (a) left plot: the tube contribution; (b) middle plot: the one from the background (blue dashed line) and the resultant correlation (black solid line) for central collisions, as given by Eq.(2); and (c) right plot: the corresponding ones for the peripheral collisions. This happens because the first term on the r.h.s. of Eq.(2) is mostly determined by the elliptic flow of the system, its magnitude increases from central to peripheral collisions, following that of the background elliptic flow v_2^b. Consequently, for peripheral collisions, it may be just big enough to fill up the "valley" of the second term, which results in a single peak on the away-side as shown by the black curve in the third plot.

2 Results and discussions

The purpose of the peripheral-tube model is to show in a clear-cut way how several characteristics of the so-called ridge phenomena are produced. Being so, although extracted from the more realistic studies, for the sake of clarity, only essential ingredients are retained in the model, namely,

- The collective flow consists of contributions from the background and those induced by randomly distributed peripheral tubes. For simplicity and clearness, here we consider just one such tube. The main difference, if one has more than one peripheral tube, is that in the latter case (even in the central collisions), the flow parameters (v_n and Ψ_n) are largely spread event-by-event, although the final two-particle correlation is almost independent of the number of tubes.
- The background elliptic-flow coefficient increases from central to peripheral collisions, while the multiplicity decreases.
- Event-by-event fluctuation is reflected in the model in two aspects: first, the azimuthal location of the tube is randomized from event to event and, second, the background multiplicity fluctuates from event to event.

Recall that experimentally the background multiplicity always fluctuates and this is important to be considered in the correlation calculation, as will become clear later. We write down the one-particle distribution as a sum of two contributions: the distribution of the background and that of the tube.

$$\frac{dN}{d\phi}(\phi,\phi_t) = \frac{dN_{bgd}}{d\phi}(\phi) + \frac{dN_{tube}}{d\phi}(\phi,\phi_t), \tag{1}$$

where the two distributions are normalized to N_b and N_t, and are expaneded in terms of flow coefficients v_2^b, v_2^t, v_3^t with superscripts b for background flow and t for the tube. We assume that the tube is located in the azimuthal angle ϕ_t according to the probability distribution $f(\phi_t)$.
Following the methods used by PHENIX Collaboration [3], the subtracted di-hadron correlation is given by

$$\left\langle \frac{dN_{\rm pair}}{d\Delta\phi} \right\rangle = \left\langle \frac{dN_{\rm pair}}{d\Delta\phi} \right\rangle^{\rm proper} - \left\langle \frac{dN_{\rm pair}}{d\Delta\phi} \right\rangle^{\rm mixed}. \tag{2}$$

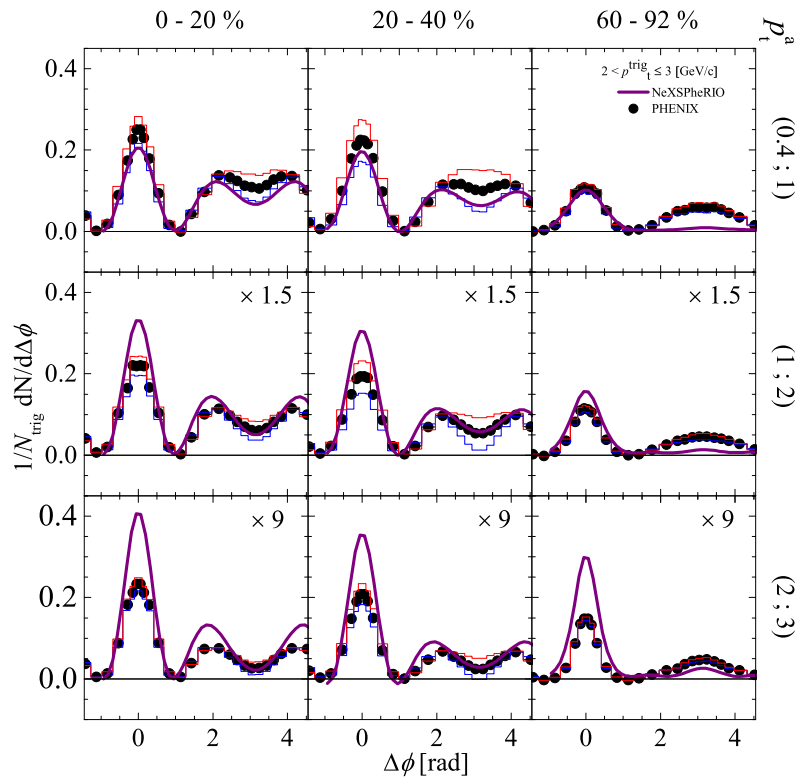
In peripheral tube model,

$$\left\langle \frac{dN_{\rm pair}}{d\Delta\phi} \right\rangle^{\rm proper} = \int \frac{d\phi_s}{2\pi}\frac{d\phi_t}{2\pi} f(\phi_t) \frac{dN}{d\phi}(\phi_s,\phi_t)\frac{dN}{d\phi}(\phi_s+\Delta\phi,\phi_t), \tag{3}$$

where ϕ_s is the azimuthal angle of the trigger particle. We will take $f(\phi_t) = 1$, for simplicity.
The combinatorial background $\langle dN_{\rm pair}/d\Delta\phi\rangle^{\rm mixed}$ can be calculated by using the ZYAM method. Straightforward calculations give

$$\left\langle \frac{dN_{\rm pair}}{d\Delta\phi}(\phi_s) \right\rangle^{\rm (ZYAM)} = \frac{\langle N_b^2\rangle - B\langle N_b\rangle^2}{(2\pi)^2}(1 + 2(v_2^b)^2\cos(2\Delta\phi)) + (\frac{N_t}{2\pi})^2 \sum_{n=2,3} 2{v_n^t}^2\cos(n\Delta\phi). \tag{4}$$

The results shown in the previous figure are obtained with a reasonable choice of the model parameters.



In order to show that a hydrodynamical description indeed captures the main physical content of the observed data, we present, in the above plot, the results of numerical simulations by using the hydrodynamic code NeXSPheRIO. In our calculations, the di-hadron correlations are obtained by the ZYAM method and compared to the data by PHENIX Collaboration.

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