Centrality, azimuthal and rapidity dependence of two-particle transverse-momentum correlation in relativistic heavy ion collisions*

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Abstract The centrality, azimuthal and rapidity dependence of two-particle transverse-momentum correlations are studied for Au-Au collision at 200 GeV using RQMD (relativistic quantum molecular dynamics) with and without final hadron re-scattering models. The influences of the re-scattering effects on the measured correlations are discussed. The results are compared with those from current heavy ion experiments.

Key words centrality, azimuthal, rapidity, transverse-momentum, correlation.

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1 Introduction

Since transverse momenta of the final state particles are produced after the collision and carry the information of system expansion, their fluctuations are considered to be a good probe for the formation of quark-gluon plasma (QGP)[1, 2] and a trace of local thermal equilibrium[3]. Therefore, these fluctuations have drawn a lot of attention in both theoretical and experimental investigations of relativistic heavy ion collisions[4].

Since the first measure of transverse momentum fluctuation was suggested[5], a number of other ones have been recommended[3, 6—12] to extract the genuine dynamical fluctuations, such as, Φ_{p_t}[5, 13], $\sigma^2_{\text{dynamic}}$[14], Σ_{p_t}[6], F_{p_t}[7], and $\Delta\sigma^2_{p_t,n}$[15]. These measures are related with each other under some approximate conditions[16], but they have very different dependence on experimental acceptance, in particular, the rapidity and azimuthal acceptance[13]. A quantitative study requires a standard formalism to facilitate a comparison of results among different experiments and theory. Fortunately, no matter how complicated those measures are, the common and essential part among them is the event two-particle transverse momentum correlation $\langle \Delta p_{t_i} \Delta p_{t_j} \rangle$. Hence, in the following, we will focus only on this most simple correlation.

In this paper, we study the centrality, azimuthal and rapidity dependency of this two-particle transverse-momentum correlation for Au-Au collision at $\sqrt{S_{\text{NN}}} = 200$ GeV using RQMD with and without hadron re-scattering models. The effects of final hadron re-scattering are discussed.

2 On the normalization of two-particle transverse-momentum correlation

There are two schemes to normalize two-particle correlation, $\langle \Delta p_{t_i} \Delta p_{t_j} \rangle$. One is to normalize by the number of correlation pairs $n_{\text{ch}}(n_{\text{ch}}-1)$ of each event and the average of event mean transverse momentum $\langle \bar{p}_t \rangle$, i.e.,

$$\langle \Delta p_{t_i} \Delta p_{t_j} \rangle = \left\langle \frac{\sum_{i=1}^{n_{\text{ch}}} \sum_{j=1, i\neq j}^{n_{\text{ch}}} (p_{t_i} - \langle \bar{p}_t \rangle)(p_{t_j} - \langle \bar{p}_t \rangle)}{n_{\text{ch}}(n_{\text{ch}}-1)} \right\rangle \Big/ \langle p_t \rangle^2,$$

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which is used by the STAR Collaboration[8]. Where $n_{\rm ch}$ is the number of charged particles and $p_{{\rm t}_i}$ is the transverse momentum of the ith particle. The correlation defined in this way is referred to as event mean two-particle transverse momentum correlation. It is one unit more than the measure,

$$R\left(p_{{\rm t}_i},p_{{\rm t}_j}\right)=\left\langle \frac{\sum\limits_{i=1}^{n_{\rm ch}}\sum\limits_{j=1,i\neq j}^{n_{\rm ch}} p_{{\rm t}_i}p_{{\rm t}_j}}{n_{\rm ch}(n_{\rm ch}-1)}\right\rangle \frac{1}{\langle\bar{p}_{\rm t}\rangle^2} \ . \qquad (1)$$

Another scheme is to normalize the correlation by the average number of correlation pairs $\langle n_{\rm ch}(n_{\rm ch}-1)\rangle$ and the inclusive mean transverse momentum $\langle p_{\rm t}\rangle$[11, 12], i.e., $\langle \Delta p_{{\rm t}_i}\Delta p_{{\rm t}_j}\rangle=\langle\sum\limits_{i=1}^{n_{\rm ch}}\sum\limits_{j=1,i\neq j}^{n_{\rm ch}}(p_{{\rm t}_i}-\langle p_{\rm t}\rangle)(p_{{\rm t}_j}-\langle p_{\rm t}\rangle)\rangle/[\langle n_{\rm ch}(n_{\rm ch}-1)\rangle\langle p_{\rm t}\rangle^2]$. This normalization is strongly recommended by S. Voloshin et al., as it is directly related to the well defined two-particle transverse momentum correlation and is not as the so-called ratio-like observable R. However, it is not directly related to the corresponding two-particle correlation,

$$R'\left(p_{{\rm t}_i},p_{{\rm t}_j}\right)=\frac{\left\langle \sum\limits_{i=1}^{n_{\rm ch}}\sum\limits_{j=1,i\neq j}^{n_{\rm ch}} p_{{\rm t}_i}p_{{\rm t}_j}\right\rangle}{\langle n_{\rm ch}\left(n_{\rm ch}-1\right)\rangle\langle p_{\rm t}\rangle^2} \ , \qquad (2)$$

since it contains an extra $p_{\rm t}$-$n_{\rm ch}$ correlation.

The main differences between these two normalization schemes are the total pairs of each event and the average total pairs of all events, and the event mean transverse-momentum and the average single particle transverse-momentum. The event mean transverse momentum is defined as $\bar{p}_{{\rm t}_k}=\sum\limits_i p_{{\rm t}_i}/n_k$. Its sample average is

$$\langle\bar{p}_{\rm t}\rangle=\frac{1}{N_{\rm event}}\sum_{k=1}^{N_{\rm event}}\bar{p}_{{\rm t}_k} \ , \qquad (3)$$

where n_k is the charge multiplicity in the kth event and $N_{\rm event}$ is the number of events. It is different from the mean single particle transverse-momentum,

$$\langle p_{\rm t}\rangle=\frac{1}{N_{\rm event}}\sum_{k=1}^{N_{\rm event}}\sum_{i=1}^{n_k}p_{{\rm t}_{ik}} \ , \qquad (4)$$

due to the correlations between multiplicity and transverse momentum. They are equal only for the sample with fixed multiplicity.

3 The centrality, azimuthal and rapidity dependence of event-by-event transverse-momentum correlation

The RQMD (relativistic quantum molecular dynamics) is a hadron-based transport model[17]. The final hadron interactions are implemented in the model by hadron re-scattering. Although the anisotropic collective flow produced by the model is much smaller than the observed data at RHIC, we can still see whether the suggested transverse-momentum correlation is sensitive to the centrality of collisions and acceptance in this kind of transport model.

The data used in this analysis include 3 million events with re-scattering and without re-scattering at 200 GeV for Au-Au collision. The centrality bins were calculated as a fraction of the multiplicity of all charged particles measured with $|\eta|<0.5$. They are, 0—5% (for the most central), 10%—20%, 20%—30%, 30%—40%, 50%—60%, and 70%—80%. Each centrality corresponds to a number of participating nucleons $N_{\rm part}$, which can be estimated by the Monte Carlo of the Glauber model[18].

3.1 Centrality dependency

The centrality dependencies of the inclusive mean transverse momentum $\langle p_{\rm t}\rangle$ and the two-particle transverse momentum correlation R are shown in Fig. 1(a) and (b) respectively, where the solid circles and triangles are, respectively, the results of RQMD with and without re-scattering (this convention will be kept in all the following figures). Obviously, the mean transverse momentum $\langle p_{\rm t}\rangle$, as shown in Fig. 1(a), increases with centrality. It shows that the final hadron re-scattering makes the transverse expansion strong, in particular, in the most central collision where the re-scattering effect is greatly enhanced. However, two-particle transverse momentum correlation decreases with centrality, which is consistent with the results given by the STAR experiment[19].

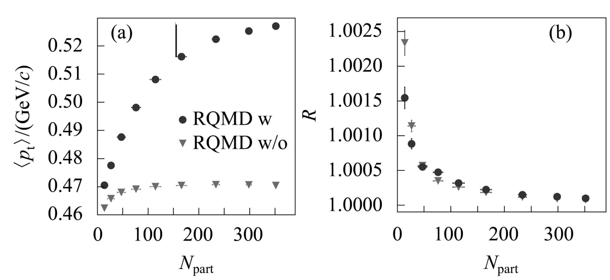

Fig. 1. The centrality dependence of the inclusive mean transverse momentum $\langle p_{\rm t}\rangle$ (a) and two-particle transverse momentum correlation R (b), selecting charge particles with $|\eta|<1$ and $0.15<p_{\rm t}<2.0$.

Those results show that the inclusive mean transverse momentum and the two-particle transverse momentum correlation have reverse centrality dependency, and the final hadron re-scattering contributes a lot to the single particle transverse momentum distribution, but has little influence on the strength of two-particle transverse momentum correlation.

3.2 Azimuthal dependency

In order to see how the size of the azimuthal observed window influences the two-particle transverse momentum correlation, the azimuthal dependency of the correlation at the most central 0—5% and non-central 40%—50% collisions are shown in the lower and upper panels of Fig. 2, respectively. The results for all charge particles, charge particles in $|\eta| < 1$ and charge particles within $|\eta| < 1$, and $0.15 < p_t < 2.0$, corresponding to the acceptance of the STAR TPC[20], are presented in Fig. 2(a), (b) and (c), respectively. $\Delta\phi$ is the size of the azimuthal window.

In both Fig. 2(a) and Fig. 2(b), the two-particle transverse momentum correlation first decreases rapidly with the acceptance of the azimuthal angle and then increases slightly at $\Delta\phi \approx \pi$, at $\Delta\phi > 4$ it reaches a saturation with further increase in the size of the azimuthal window. These show that the influence of the limited size of the azimuthal observed angle is not negligible when the observed azimuthal window $\Delta\phi < 4$. For both the central and non-central collisions, these azimuthal dependencies of the correlation are similar and therefore, the azimuthal dependence of the correlation is independent of the choice of centrality.

In Fig. 2(c), the correlation is almost independent of the azimuthal acceptance for the most central collision, this is consistent with the result of the most central Pb-Au collisions of the CERES experiment[6]. This result indicates that the transverse-momentum correlation of soft particles is insensitive to finite the size of the azimuthal acceptance in the most central collision, contrary to that for all p_t particles.

These results show that the two-particle transverse momentum correlation is strongly influenced by the azimuthal acceptance, but reaches saturation at the azimuthal acceptance window $\Delta\phi > 4$. The azimuthal dependence is insensitive to the cuts of pseudo-rapidity but sensitive to the selected range of transverse-momentum of the final state particles. The final hadron re-scattering and centrality of the collisions have little influence on the azimuthal dependence of two-particle transverse-momentum correlation.

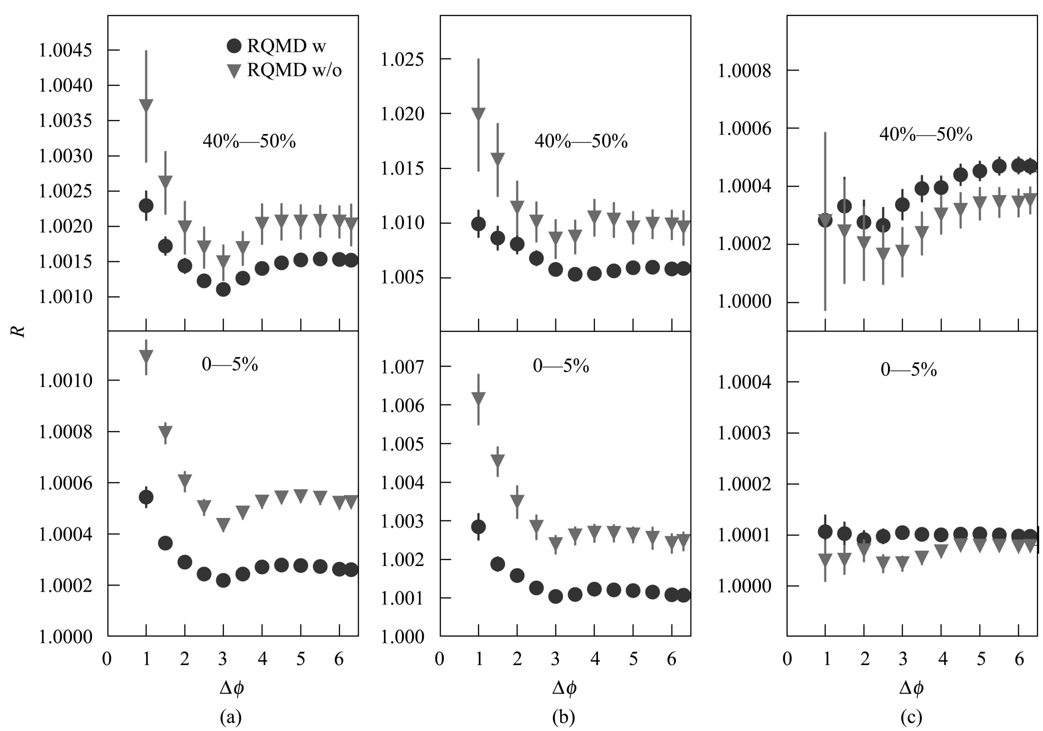

Fig. 2. The two-particle transverse momentum correlation R as a function of the azimuthal acceptance window $\Delta\phi$, for three samples: (a) all charge particles; (b) charge particles in $|\eta| < 1$; (c) charge particles with $|\eta| < 1$ and $0.15 < p_t < 2.0$.

3.3 Rapidity dependency

The rapidity dependencies of the two-particle transverse momentum correlation R and R' are shown in Fig. 3(a) and (b), respectively, where all charge particles are selected. The correlation R decreases with the size of the central rapidity window. The hadron re-scattering does not influence the rapidity dependence of R. While the correlation R' has little dependence on the observed rapidity window, the correlation strength changes greatly by the hadron re-scattering effects. This is because the R' is normalized by average single transverse-momentum, which is the measure of transverse expansion. The rapidity dependence of R and R' are contrary to those of the hadron-hadron collisions[21].

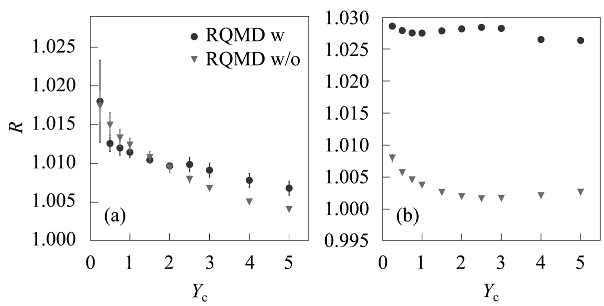

Fig. 3. The rapidity dependence of two-particle transverse momentum correlation for two normalization schemes.

4 Summary

The centrality, azimuthal and rapidity dependences of two-particle transverse-momentum correlations are studied for Au-Au collisions at 200 GeV using RQMD with and without final hadron re-scattering models. We find that: (1) The mean inclusive transverse-momentum and two-particle transverse-momentum correlation have opposite centrality dependence. Final hadron re-scattering has little influence on two-particle transverse-momentum correlation, but contributes greatly to the mean inclusive transverse-momentum. (2) The two-particle transverse-momentum correlation depends obviously on the size of the azimuthal observed window. Such dependence becomes negligible when the size of the azimuthal angle is larger than 4, or, the observed particles are constrained to the soft particles in the most central collisions. The final hadron re-scattering has little influence on the azimuthal dependence of the correlation. (3) The strength of two-particle transverse-momentum correlation decreases with the size of the rapidity window. Therefore, the acceptance effects have to be taken into account in the measured transverse-momentum correlations.

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