Multiplicity moments and hard processes in relativistic heavy ion collisions

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The normalized multiplicity moments and their relation with soft and hard processes in relativistic heavy ion collisions are analyzed in a general two-component model. It is found that the strong fluctuations in the binary collision number N_c in minimum-bias events can enhance the hard component, especially for the higher order moments. This enhancement cannot be effectively described by modifying the participant number in the one-component model.

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I. INTRODUCTION

The relativistic heavy ion collisions at SPS and RHIC may be the only way to create the extreme conditions necessary to produce a new state of matter—quark-gluon plasma in the laboratory [1,2]. One can attempt to understand the energy density achieved in the collisions by studying the multiplicity and transverse energy distributions through hydrodynamic models [3]. At SPS energies, the global quantities, such as average multiplicity, multiplicity distribution, and rapidity distribution, can be well described by soft processes only, namely, by the number of participant nucleons only [4]. However, at RHIC energies, the measured pseudorapidity density normalized per participant pair for central Au-Au collisions shows that 70% more particles are produced than at SPS [5,6]. This indicates that the yield of particles created by hard scattering processes becomes important at RHIC [1,7]. One can decompose the multiplicity at a fixed impact parameter into a soft component and a hard component as [1,6,8]

$$n = aN_p + bN_c\,, \tag{1}$$

where N_p and N_c are the participant number and binary collision number, respectively.

However, the two-component expression (1) can be effectively described by a simple power-law form

$$n = cN_p^{\alpha}, \quad \alpha > 1, \tag{2}$$

which is then similar to that measured at SPS [9]. A natural question then arises: Can one find other global observables which are more sensitive to the hard processes than the multiplicity itself, and which cannot be effectively described in the models with only soft processes?

As is well known, the multiplicity moments are important characteristics in multiparticle production. The properties of the multiplicity distribution can be completely described by the normalized moments

$$C_i = \frac{\langle n^i\rangle}{\langle n\rangle^i}, \quad i = 2,3,\ldots\,. \tag{3}$$

In Ref. [10] C_i were investigated at SPS energies with a general wounded nucleon model. It was found that the normalized multiplicity moments are independent of the concrete behavior of elementary nucleon-nucleon collisions, but dominated by the normalized participant moments

$$C_i \simeq C_{ip} = \frac{\langle N_p^i\rangle}{\langle N_p\rangle^i}, \tag{4}$$

provided that the colliding nuclei are not too light.

In this paper we investigate how the hard processes change the normalized multiplicity moments. We extend the study in Ref. [10] to include the hard component. We will focus on the sensitivity of C_i to the colliding energy, nuclear geometry, and especially to the geometry fluctuations.

II. MULTIPLICITY MOMENTS

If the average multiplicity distribution of each soft source is $g_p(n_p)$, and the average multiplicity distribution of each hard source is $g_c(n_c)$, the multiplicity distribution of an AB collision is the supposition of the contributions of N_p soft sources and N_c hard sources:

$$G_{N_p,N_c}(n) = \sum_{\substack{n_p^{(1)},\ldots,n_p^{(N_p)} \\ n_c^{(1)},\ldots,n_c^{(N_c)}}} \delta\left(n - \sum_{i=1}^{N_p} n_p^{(i)} - \sum_{j=1}^{N_c} n_c^{(j)} \right) \prod_{i=1}^{N_p} g_p(n_p^{(i)}) \prod_{j=1}^{N_c} g_c(n_c^{(j)}). \tag{5}$$

It will be seen later that the results in this paper are not concerned with the concrete form of $g_p(n_p)$ and $g_c(n_c)$. Taking into account all the processes with different N_p and N_c, the observed multiplicity distribution is

$$P(n) = \sum_{N_p,N_c} p(N_p,N_c)\, G_{N_p,N_c}(n), \tag{6}$$

where $p(N_p,N_c)$ is the distribution function of N_p and N_c.

At fixed impact parameter b, the nuclear geometry of soft and hard processes is expressed in terms of $N_p(b)$ and $N_c(b)$ [11], respectively,

$$N_p(b)=\int d^2\mathbf{s}[T_A(\mathbf{s})(1-e^{-\sigma_N T_B(\mathbf{b}-\mathbf{s})})+T_B(\mathbf{b}-\mathbf{s})(1-e^{-\sigma_N T_A(\mathbf{s})})],$$

$$N_c(b)=\int d^2\mathbf{s}\sigma_N T_A(\mathbf{s})T_B(\mathbf{b}-\mathbf{s}), \tag{7}$$

where σ_N is the nucleon-nucleon inelastic cross section, and $T_A(\mathbf{s})$ and $T_B(\mathbf{b}-\mathbf{s})$ are the local participant densities in the plane orthogonal to the collision axis defined as

$$T_A(\mathbf{s})=\int dz\rho_A(\mathbf{s},z),$$

$$T_B(\mathbf{b}-\mathbf{s})=\int dz\rho_B(\mathbf{b}-\mathbf{s},z). \tag{8}$$

Since $N_c(b)$ calculated with Eq. (7) is a monotonic function of $N_p(b)$, the distribution of $N_p(b)$ and $N_c(b)$, $p(N_p(b),N_c(b))$, is just the distribution of $N_p(b)$, which can be obtained from Eq. (7) as

$$p(N_p(b),N_c(b))\sim\frac{b}{dN_p(b)/db}. \tag{9}$$

When b is fixed, the stochastic variables N_b and N_c in Eq. (6) still have fluctuations around $N_p(b)$ and $N_c(b)$. For simplicity, we use the Gaussian distribution to describe the stochastic fluctuations,

$$p(N_p|N_p(b))=\frac{1}{\sqrt{2\pi\sigma_p^2(b)}}e^{-[N_p-N_p(b)]^2/2\sigma_p^2(b)},$$

$$p(N_c|N_c(b))=\frac{1}{\sqrt{2\pi\sigma_c^2(b)}}e^{-[N_c-N_c(b)]^2/2\sigma_c^2(b)}, \tag{10}$$

with the variances

$$\sigma_p^2(b)=a_pN_p(b),$$

$$\sigma_c^2(b)=a_cN_c(b), \tag{11}$$

where a_p and a_c are constants. Considering both the geometry fluctuations (9) and the stochastic fluctuations (10), the probability of the stochastic variables N_p and N_c in Eq. (6) is given by

$$p(N_p,N_c)=\sum_{N_p(b)\geqslant N_{min}}p(N_p|N_p(b))p(N_c|N_c(b))p(N_p(b),N_c(b)), \tag{12}$$

where we have used the minimum participant number N_{min} to select events. $N_{min}=2$ means minimum-bias events and very large N_{min} corresponds to central events.

We introduce now generating functions [10,12] $F(\theta),f_p(\theta)$, and $f_c(\theta)$ for the whole system and the elementary soft and hard sources,

$$F(\theta)\equiv\sum_n\theta^nP(n)=\sum_{N_p,N_c}p(N_p,N_c)[f_p(\theta)]^{N_p}[f_c(\theta)]^{N_c},$$

$$f_p(\theta)\equiv\sum_{n_p}\theta^{n_p}g_p(n_p),$$

$$f_c(\theta)\equiv\sum_{n_c}\theta^{n_c}g_c(n_c),\quad -1\leqslant\theta\leqslant 1. \tag{13}$$

Differentiating Eq. (13) with respect to θ and making use of the relations

$$F(\theta)|_{\theta=1}=f_p(\theta)|_{\theta=1}=f_c(\theta)|_{\theta=1}=1,$$

$$\frac{\partial}{\partial\theta}F(\theta)|_{\theta=1}=\langle n\rangle,$$

$$\frac{\partial}{\partial\theta}f_p(\theta)|_{\theta=1}=\langle n_p\rangle,$$

$$\frac{\partial}{\partial\theta}f_c(\theta)|_{\theta=1}=\langle n_c\rangle,$$

$$\frac{\partial^2}{\partial\theta^2}F(\theta)|_{\theta=1}=\langle n(n-1)\rangle,$$

$$\frac{\partial^2}{\partial\theta^2}f_p(\theta)|_{\theta=1}=\langle n_p(n_p-1)\rangle,$$

$$\frac{\partial^2}{\partial\theta^2}f_c(\theta)|_{\theta=1}=\langle n_c(n_c-1)\rangle,\ \dots, \tag{14}$$

we derive the multiplicity moments $\langle n^i\rangle$ in terms of the elementary soft and hard moments $\langle n_p^i\rangle$ and $\langle n_c^i\rangle$ and the nuclear geometry moments $\langle N_p^i\rangle,\langle N_c^i\rangle$, and $\langle N_p^iN_c^j\rangle$,

$$\langle n\rangle=\langle N_p\rangle\langle n_p\rangle+\langle N_c\rangle\langle n_c\rangle,$$

$$\langle n^2\rangle=(\langle N_p^2\rangle-\langle N_p\rangle)\langle n_p\rangle^2+\langle N_p\rangle\langle n_p^2\rangle+(\langle N_c^2\rangle-\langle N_c\rangle)\langle n_c\rangle^2+\langle N_c\rangle\langle n_c^2\rangle+2\langle N_pN_c\rangle\langle n_p\rangle\langle n_c\rangle,$$

$$\begin{aligned}\langle n^3\rangle={}&(\langle N_p^3\rangle-3\langle N_p^2\rangle+2\langle N_p\rangle)\langle n_p\rangle^3+3(\langle N_p^2\rangle-\langle N_p\rangle)\langle n_p\rangle\\&\times\langle n_p^2\rangle+\langle N_p\rangle\langle n_p^3\rangle+(\langle N_c^3\rangle-3\langle N_c^2\rangle+2\langle N_c\rangle)\langle n_c\rangle^3\\&+3(\langle N_c^2\rangle-\langle N_c\rangle)\langle n_c\rangle\langle n_c^2\rangle+\langle N_c\rangle\langle n_c^3\rangle\\&+3(\langle N_p^2N_c\rangle-\langle N_pN_c\rangle)\langle n_p\rangle^2\langle n_c\rangle+3(\langle N_pN_c^2\rangle\\&-\langle N_pN_c\rangle)\langle n_p\rangle\langle n_c\rangle^2+3\langle N_pN_c\rangle\langle n_p^2\rangle\langle n_c\rangle\\&+3\langle N_pN_c\rangle\langle n_p\rangle\langle n_c^2\rangle,\ \dots,\end{aligned} \tag{15}$$

with the definitions of the moments,

$$\langle n^i\rangle=\sum_n n^i P(n)/\sum_n P(n),$$

$$\langle n_p^i\rangle=\sum_{n_p} n_p^i g(n_p)/\sum_{n_p} g(n_p),$$

$$\langle n_c^i\rangle=\sum_{n_c} n_c^i g(n_c)/\sum_{n_c} g(n_c),$$

$$\langle N_p^i N_c^j\rangle=\sum_{N_p,N_c} N_p^i N_c^j p(N_p,N_c)/\sum_{N_p,N_c} p(N_p,N_c). \quad (16)$$

With the known multiplicity moments, the normalized moments $C_i=\langle n^i\rangle/\langle n\rangle^i$ can be expressed as an expansion in the inverse number of average participants $1/\langle N_p\rangle$,

$$C_i=\frac{\left\langle\left(\frac{N_p}{\langle N_p\rangle}+\frac{N_c}{\langle N_c\rangle}x\right)^i\right\rangle}{(1+x)^i}+O\left(\frac{1}{\langle N_p\rangle}\right), \quad (17)$$

where the average ratio of the hard to soft component

$$x=\frac{\langle N_c\rangle\langle n_c\rangle}{\langle N_p\rangle\langle n_p\rangle} \quad (18)$$

depends on the elementary nucleon-nucleon dynamics and the nuclear geometry. If we do not consider peripheral interactions alone, $\langle N_p\rangle,\langle N_c\rangle\gg 1$, we can then consider only the zeroth order in the expansion (17). In this case, only the average ratio of the hard to soft component remains, the other dynamics of elementary soft and hard processes hidden in $\langle n_p^i\rangle$ and $\langle n_c^i\rangle$ with $i>2$ is washed away by the nuclear geometry.

When the hard contribution can be neglected, namely, $x\to 0$, the normalized multiplicity moments are just the normalized participant moments

$$C_i=C_{ip}=\frac{\langle N_p^i\rangle}{\langle N_p\rangle^i}. \quad (19)$$

This is the case discussed in Ref. [10] at SPS energies.

III. NUCLEAR GEOMETRY AND ENERGY DEPENDENCE OF HARD CONTRIBUTION

Let us first determine the soft and hard components $\langle n_p\rangle$ and $\langle n_c\rangle$ in elementary nucleon-nucleon collisions. To this end, we compare the average multiplicity with the experimental data for central Au-Au collisions. Since we did not introduce rapidity dependence in our discussion, we consider only the central rapidity region where the data show a plateau structure. By comparing the average participant number $\langle N_p\rangle$, the average multiplicity per participant pair,

$$\frac{\langle n\rangle}{0.5\langle N_p\rangle}=2\langle n_p\rangle(1+x), \quad (20)$$

and the multiplicity for $P\bar{P}$,

TABLE I. The ratio x of the hard to soft component and the geometry parameter N_{min} determined from the comparison with the data of central Au-Au collisions at RHIC.

$\sqrt{s}$	$\langle N_p\rangle$	$\frac{\langle N\rangle}{0.5\langle N_p\rangle}$	N_{min}	x
56	330	2.47	297	0.32
130	343	3.24	323	0.58
200	344	3.78	326	0.74

$$\langle n_{P\bar{P}}\rangle=2\langle n_p\rangle+\langle n_c\rangle, \quad (21)$$

with the experimental data [5,13] in the central rapidity region $|\eta|<1$ at RHIC and the parametrization of the $P\bar{P}$ data [14],

$$\langle n\rangle_{P\bar{P}}=2.5-0.25\ln s+0.023\ln^2 s, \quad (22)$$

we can determine at different energies the average ratio x and the minimum participant number N_{min} which is used to select centrality in calculating geometry moments. Using a Woods-Saxon distribution

$$\rho_A(\mathbf{r})=\frac{\rho_0}{1+e^{(r-R_A)/a}}, \qquad \int d^3\mathbf{r}\rho_A(\mathbf{r})=A, \quad (23)$$

with the parameters $a=0.53$ fm, $R_A=1.1A^{1/3}$ fm for ^{197}Au, taking $\sigma_N=37$ mb at $\sqrt{s}=56A$ GeV ($\sigma_N=41$ mb for $\sqrt{s}=130{,}200$ A GeV) [8], and choosing the constants a_p and a_c in the variances of the Gaussian distributions (10) to be $a_p=a_c=1$, the two parameters are shown in Table I. We see that at RHIC energies, $x<1$, the soft component is still more important than the hard component. In our numerical calculations, when we change the variance parameters a_p and a_c from 0.1 to 1, the ratio x determined using Eqs. (20)–(22) remains almost a constant, but N_{min} increases with increasing a_p and a_c. Taking $a_p=a_c=0.1$, N_{minb} is 289, 314, and 316 corresponding to colliding energy $\sqrt{s}=56{,}130$, and 200 GeV. The change in N_{min} will certainly lead to a considerable change in the moments $\langle N_p^i N_c^j\rangle$, especially for the minimum-bias events, but our numerical calculations show that the normalized moments C_i and C_{ip} are not sensitive to the variance parameters a_p and a_c.

The influence of nuclear geometry is twofold: The average numbers $\langle N_p\rangle$ and $\langle N_c\rangle$ and the fluctuations of N_p and N_c around their average values. For central collisions the average numbers $\langle N_p\rangle$ and $\langle N_c\rangle$ are huge, but the fluctuations are small. This can be seen clearly in Table I where $\langle N_p\rangle\geqslant 330$ and $291\leqslant N_p(b)\leqslant N_p(b=0)$. From the Gaussian distributions (10), when $N_p(b)$ and $N_c(b)$ vary in such a narrow region, the stochastic variables N_p and N_c fluctuate only around this small region. For minimum-bias events the average numbers are relatively small, but the fluctuations are the maximum.

The multiplicity $\langle n\rangle$ is only related to the average values $\langle N_p\rangle$ and $\langle N_c\rangle$. When the hard contribution vanishes, the average multiplicity is proportional to $\langle N_p\rangle$. The hard con-

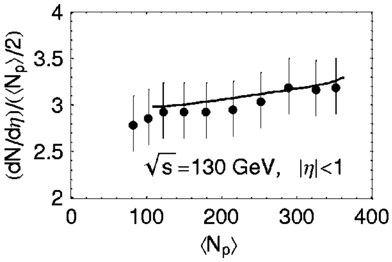

FIG. 1. The centrality dependence of the average multiplicity normalized to per participant pair and its comparison with the RHIC data.

tribution reflected in the ratio x leads to an extra $\langle N_c\rangle$ dependence. The centrality dependence of the average multiplicity per participant pair (20) can be calculated by changing the minimum participant number N_{min} from 2 to $N_p(b=0)$. In Fig. 1 it is compared with the data in the central rapidity region $|\eta|<1$ for the central Au–Au collisions at $\sqrt{s}=130A$ GeV [15]. The extra geometry dependence induced by the hard component is weak.

Since $\langle N_p^i\rangle = \langle (N_p/\langle N_p\rangle)^i\rangle\langle N_p\rangle^i$ and $\langle N_c^i\rangle = \langle (N_c/\langle N_c\rangle)^i\rangle\langle N_c\rangle^i$, the multiplicity moments $\langle n^i\rangle$ for $i\geqslant 2$ are associated with both the average numbers $\langle N_p\rangle$ and $\langle N_c\rangle$ and the fluctuations in N_p and N_c. From Eq. (17) the normalized moments C_i depend on the fluctuations and the average ratio x of the hard to soft component. Figure 2 shows the centrality and energy dependence of x. At any energy the centrality dependence is very weak. Therefore, the behavior of the normalized moments C_i is mainly controlled by the fluctuations in N_p and N_c. Let us first consider the limit of no fluctuations, $N_p=\langle N_p\rangle, N_c=\langle N_c\rangle$. In this limit,

$$p(N_p)=\delta_{N_p\langle N_p\rangle}, \tag{24}$$

we have

$$C_i=C_{ip}=1. \tag{25}$$

In this case there is no difference between the two-component and one-component model. Although fluctuations around the average numbers always exist, and it is difficult to choose events with the same impact parameter b, namely, with the same $N_p(b)$ and $N_c(b)$, in experiments, for very central collisions with large $\langle N_p\rangle$ and $\langle N_c\rangle$, N_p and N_c fluctuate in a narrow region, the case is then similar to the above limit.

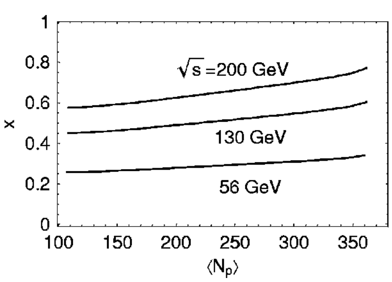

FIG. 2. The energy and centrality dependence of the average ratio x of the hard to soft component.

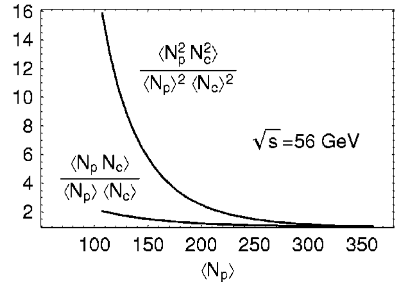

FIG. 3. The centrality dependence of the geometry fluctuations.

The fluctuations grow up when the minimum participant number N_{min} decreases from its maximum value $N_p(0)$. Figure 3 shows the centrality dependence of the fluctuations $\langle N_p^i N_c^j\rangle/\langle N_p\rangle^i\langle N_c\rangle^j$. As the orders i and j are not too small, the fluctuations are very strong for minimum-bias events.

In order to see the contribution from the hard processes, we define the ratio of the normalized moments with and without consideration of the hard component,

$$r_i=\frac{C_i}{C_{ip}}. \tag{26}$$

The centrality and energy dependence of r_i is shown in Fig. 4. While there is no remarkable difference between C_{ip} and C_i in central collisions, the big fluctuations in N_p and N_c in minimum-bias events enhance the hard contribution, and this enhancement becomes more and more important when the colliding energy increases. At $\sqrt{s}=200A$ GeV, the hard contribution to C_5 is larger than 50%.

In order to see the contribution of the fluctuations of the stochastic variables N_p and N_c around $N_p(b)$ and $N_c(b)$ at a fixed impact parameter b, we recalculated the ratio r_i without considering the Gaussian distributions (10). From the comparison shown in Fig. 5, the difference between with and without stochastic fluctuations lies mainly in minimum-bias events.

To search for nonstatistical fluctuations in the distributions of secondary particles in high energy interactions, the method of factorial moments was introduced by Bialas and Peschanski [16]. The pseudorapidity bin $\delta\eta$ dependence of the factorial moments F_i in relativistic heavy ion collisions at SPS can be well described by a linear fit [17]

$$\ln F_i=\beta_i+\alpha_i(-\ln\delta\eta). \tag{27}$$

The rapidity bin independent intersect β_i can be calculated in our global model. When the hard contribution is neglected at SPS energies, we have to the zeroth order of $1/\langle N_p\rangle$,

$$\beta_i=\ln F_{iP},$$

$$F_{iP}=\frac{\langle N_p(N_P-1)\cdots(N_P-i+1)\rangle}{\langle N_P\rangle^i}. \tag{28}$$

Table II shows the comparison between our calculation with $N_{min}=10$ and the experimental data [17] for O-Ag/Br. The calculation agrees with the data reasonably well. Since we did not consider the rapidity dependence of the soft and hard

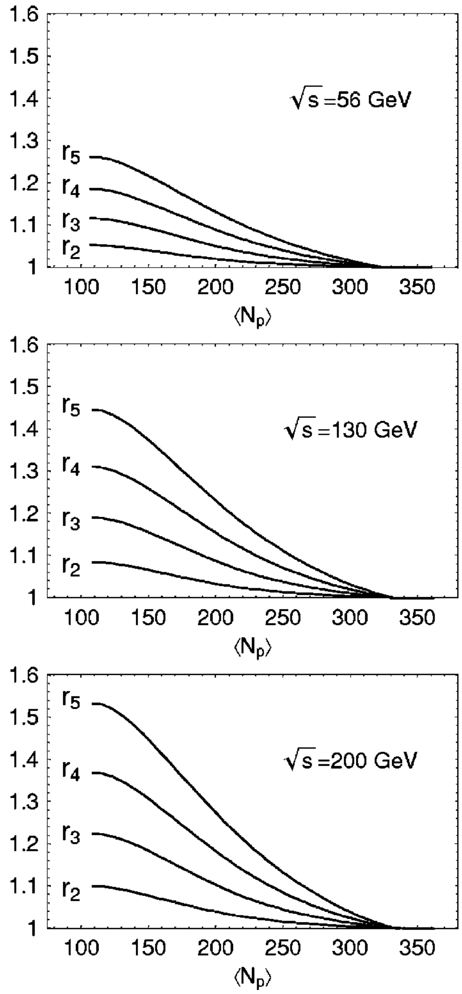

FIG. 4. The ratio of the two-component to one-component normalized moment as a function of the centrality.

sources in our global model, we cannot distinguish different rapidity bins, and therefore we cannot calculate the interesting slope parameter α_i . Its calculation depends on the details of the distributions of N_p and N_c in momentum space.

IV. COMPARISON WITH THE EFFECTIVE MODEL WITHOUT THE EXPLICIT HARD COMPONENT

The effect of the hard scattering processes on the average multiplicity can be effectively described in the one-

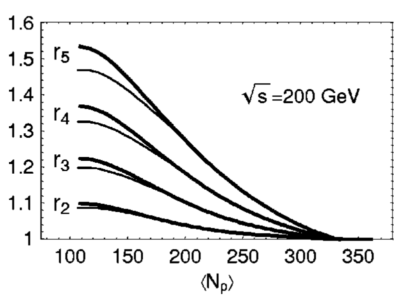

FIG. 5. The centrality dependence of r_i with (thick lines) and without (thin lines) stochastic fluctuations (10).

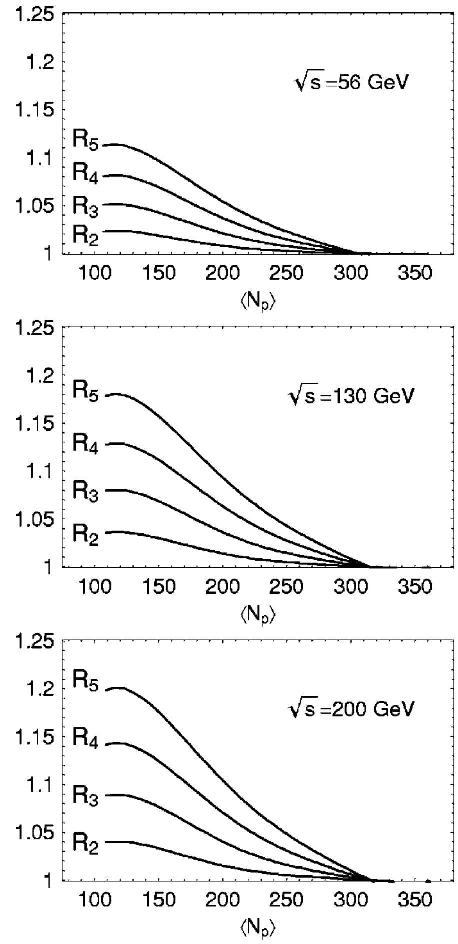

FIG. 6. The ratio of the two-component to effective one-component normalized moment as a function of the centrality.

component model by modifying the participant number [9],

$$N_c \rightarrow 0, \quad N_p \rightarrow N_p^{\alpha}, \quad \alpha > 1. \tag{29}$$

By comparing the average multiplicity $\langle n\rangle = \langle N_p^{\alpha}\rangle \langle n_p^{eff}\rangle$ with the RHIC data listed in Table I, we can determine the power α and the average contribution of each effective soft source $\langle n_p^{eff}\rangle$. Corresponding to the colliding energy $\sqrt{s}=56$, 130, 200 A GeV, we have $\alpha = 1.04$, 1.07, and 1.08, respectively.

In the effective one-component model, the normalized moments are just the effective participant moments,

$$C_i^{eff} = \frac{\langle N_p^{\alpha i}\rangle}{\langle N_p^{\alpha}\rangle^{i}}, \tag{30}$$

TABLE II. The intercept parameter β_i for O-Ag/Br. The data are taken from the KLM collaboration at $E_{lab} = 200A$ GeV and for the pseudorapidity interval $\Delta\eta = 0.5$–5.5.

i	2	3	4	5	6
Data	0.183	0.496	0.902	1.377	1.903
Model	0.190	0.501	0.877	1.282	1.691

when the peripheral interactions are not considered alone. While the contribution of the hard processes to the average multiplicity through the average binary collision number $\langle N_c \rangle$ can be equivalently expressed by increasing the average participant number from $\langle N_p \rangle$ to $\langle N_p^\alpha \rangle$, the fluctuations in N_c cannot be effectively included in the fluctuations in $\langle N_p^\alpha \rangle$. This can be seen clearly in Fig. 6, which shows the ratio

$$R_i = \frac{C_i}{C_i^{eff}} \tag{31}$$

as a function of the centrality for Au-Au collisions. From the comparison with Fig. 4, $R_i < r_i$, the fluctuations in N_c are partly included in the fluctuations in the effective participant number N_p^α. However, the difference between the two-component model and the effective one-component model is still remarkable in minimum-bias events, especially for the higher order moments and at high energies.

V. CONCLUSIONS

The huge average participant number $\langle N_p \rangle$ and binary collision number $\langle N_c \rangle$ in relativistic heavy ion collisions make it difficult to extract dynamic information on hard processes from the geometry background. Different from the multiplicity moments $\langle n^i \rangle$, which depend on both the average numbers $\langle N_p \rangle$ and $\langle N_c \rangle$ and the fluctuations in N_p and N_c strongly, the normalized moments $C_i = \langle n^i \rangle / \langle n \rangle^i$ have only weak $\langle N_p \rangle$ and $\langle N_c \rangle$ dependence, and are mainly associated with the fluctuations in N_p and N_c. Therefore, the geometry background for C_i is not so complicated as that for $\langle n^i \rangle$.

We have investigated the normalized moments C_i in the frame of a general two-component model. When the hard component can be neglected at SPS energies, C_i are completely determined by the geometry fluctuations, the dynamics is totally washed away. When the hard processes become important at RHIC energies, the average ratio of the hard to soft component depends on the centrality weakly, and C_i are dominated by the fluctuations. For central collisions where the fluctuations are weak, C_i approach 1, the dynamic information cannot be seen in C_i. However, the big fluctuations in minimum-bias events allow us to see clearly the difference between the models with and without the hard component.

While the average effect of the hard processes can be effectively described in the one-component model by modifying the participant number, we have found that the fluctuations in the binary collision number cannot be fully included in the fluctuations in the effective participant number.

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