Centrality dependence of forward-backward multiplicity correlation in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV

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We have studied the centrality dependence of charged particle forward-backward multiplicity correlation strength in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV with a parton and hadron cascade model, PACIAE, based on PYTHIA. The calculated results are compared with the STAR data. The experimentally observed correlation strength characters: (1) the approximately flat pseudorapidity dependence in central collisions and (2) the monotonous decrease with decreasing centrality are well reproduced. However the theoretical results are larger than the STAR data for the peripheral collisions. A discussion is given for the comparison among the different models and STAR data. A prediction for the forward-backward multiplicity correlation in Pb+Pb collisions at $\sqrt{s_{NN}}=5500$ GeV is also given.

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I. INTRODUCTION

The study of fluctuations and correlations has been suggested as a useful means for revealing the mechanism of particle production and Quark-Gluon-Plasma (QGP) formation in relativistic heavy ion collisions \cite{1,2}. Correlations and fluctuations of the thermodynamic quantities and/or the produced particle distributions may be significantly altered when the system undergoes phase transition from hadronic matter to quark-gluon matter because of the very different degrees of freedom between two matters.

The experimental study of fluctuations and correlations becomes a hot topic in relativistic heavy ion collisions with the availability of high multiplicity event-by-event measurements at the CERN-SPS and BNL-RHIC. An abundant experimental data have been reported \cite{3-6} where a lot of new physics arise and are urgent to be studied. A lot of theoretical investigations have been reported as well \cite{6-11}.

Recently STAR collaboration have measured the charged particle forward-backward (FB) multiplicity correlation strength $b$ in a given centrality bin size at different centralities from the most central to peripheral Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV \cite{6}. The outstanding features of STAR data are:

1. In most central collisions, the correlation strength is approximately independent of the distance between the centers of forward and backward pseudorapidity bins, $\Delta\eta$.

2. The correlation strength monotonously decreases with decreasing centrality.

3. In the peripheral collisions, the correlation strength approaches to an exponential function of $\Delta\eta$.

A lot of theoretical interests \cite{11,14} has been stimulated. The wounded nucleon model was used in \cite{12} to study the correlation strength, the first two characters of STAR data were reproduced, but the third one was not. In Ref. \cite{13}, the Glauber Monte Carlo code (GMC) with a “toy” wounded-nucleon model and the Hadron-String Dynamics (HSD) transport approach have been used to analyze the STAR data. They used three different centrality determinations: the impact parameter $b$, the number of participant (wounded) nucleons $N_{part}$, and the charged particle multiplicity $N_{ch}$ in midrapidity $|\eta|<1$. The first two characters of STAR data can be reproduced by the $N_{part}$ and $N_{ch}$ centrality determinations, while the third character can not.

We have used a parton and hadron cascade model, PACIAE, to investigate the centrality bin size dependence of charged particle multiplicity correlation in most central (5, 0-5, and 0-10%) Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV \cite{14}. It turned out that the correlation strength increases with increasing bin size. In \cite{14} we follow \cite{15} defining the charged particle FB multiplicity correlation strength $b$ as

$$b = \frac{\langle n_f n_b \rangle - \langle n_f \rangle \langle n_b \rangle}{\langle n_f^2 \rangle - \langle n_f \rangle^2} = \frac{\text{cov}(n_f, n_b)}{\text{var}(n_f)}, \quad (1)$$

where $n_f$ and $n_b$ are, respectively, the number of charged particles in forward and backward pseudorapidity bins defined relatively and symmetrically to a given pseudorapidity $\eta$. $\langle n_f \rangle$ refers to the mean value of $n_f$ for instance. $\text{cov}(n_f, n_b)$ and $\text{var}(n_f)$ are the FB multiplicity covariance and forward multiplicity variance, respectively.

In this paper we use the PACIAE model to study the charged particle FB multiplicity correlation strength

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b in a given centrality bin size at different centralities from the most central to peripheral Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. A discussion is given for the comparison among the models and STAR data as well as the STAR’s convention of different centrality determination for different measured $\Delta y$ points. A prediction for the forward-backward multiplicity correlation in Pb+Pb collisions at $\sqrt{s_{NN}}=5500$ GeV is also given.

II. THE PACIAE MODEL

The parton and hadron cascade model, PACIAE [16], is based on PYTHIA [17] which is a model for hadron-hadron (hh) collisions. The PACIAE model is composed of four stages: the parton initialization, parton evolution (rescattering), hadronization, and hadron evolution (rescattering).

1. PARTON INITIALIZATION: In the PACIAE model, a nucleus-nucleus collision is decomposed into the nucleon-nucleon collisions based on the collision geometry. A nucleon-nucleon ($NN$) collision is described with the PYTHIA model, where a $NN$ (hadron-hadron, $hh$) collision is decomposed into the parton-parton collisions. The hard parton-parton collision is described by the lowest-leading-order (LO) pQCD parton-parton cross section [18] with modification of parton distribution function in the nucleon. And the soft parton-parton interaction is considered empirically. The semihard, between hard and soft, QCD $2 \rightarrow 2$ processes are also involved in the PYTHIA (PACIAE) model. Because of the initial- and final-state QCD radiation added to the parton-parton collision processes, the PYTHIA (PACIAE) model generates a partonic multijet event for a $NN$ (hh) collision. That is followed, in the PYTHIA model, by the string-based fragmentation scheme (Lund string model and/or Independent Fragmentation model), thus a hadronic final state is reached for a $NN$ (hh) collision. However, in the PACIAE model the above fragmentation is switched off temporarily, so the result is a partonic multijet event (composed of quark pairs, diquark pairs and gluons) instead of a hadronic final state. If the diquarks (anti-diquarks) are split forcibly into quarks (anti-quarks) randomly, the consequence of a $NN$ (hh) collision is its initial partonic state composed of quarks, anti-quarks, and gluons.

2. PARTON EVOLUTION: The next stage in the PACIAE model is the parton evolution (parton rescattering). Here the $2 \rightarrow 2$ LO-pQCD differential cross sections [18] are employed. The differential cross section of a subprocess $ij \rightarrow kl$ reads

$$\frac{d\sigma_{ij\rightarrow kl}}{dt} = K \frac{\pi \alpha_s^2}{\hat{s}} \sum_{ij\rightarrow kl},$$

where the factor $K$ is introduced considering the higher order pQCD and non-perturbative QCD corrections as usual, $\alpha_s$ stands for the strong (running) coupling constant. Taking the process $q_1 q_2 \rightarrow q_1 q_2$ as an example one has

$$\sum_{q_1 q_2 \rightarrow q_1 q_2} = \frac{4 \hat{s}^2 + \hat{u}^2}{9 \hat{t}^2},$$

where $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the Mandelstam variables. Since it diverges at $\hat{t}=0$ one has to regularize it with the parton color screen mass $\mu$

$$\sum_{q_1 q_2 \rightarrow q_1 q_2} = \frac{4 \hat{s}^2 + \hat{u}^2}{9 (\hat{t} - \mu^2)^2}.$$  

The total cross section of the parton collision, $i+j$, then reads

$$\sigma_{ij}(\hat{s}) = \sum_{k,l} \int_{-\hat{s}}^{\hat{s}} dt \frac{d\sigma_{ij\rightarrow kl}}{dt}. \tag{5}$$

With the total and differential cross sections above the parton evolution (parton rescattering) can be simulated by the Monte Carlo method.

3. HADRONIZATION: The parton evolution stage is followed by the hadronization at the moment of partonic freeze-out (no any more parton collision). In the PACIAE model, the Lund string fragmentation model and phenomenological coalescence model are supplied for the hadronization of partons after rescattering. The Lund string fragmentation model is adopted in this paper. We refer to [16] for the details of the hadronization stage.

4. HADRON EVOLUTION: After hadronization the rescattering among produced hadrons is dealt with the usual two-body collision model. Only the rescattering among $\pi, k, p, n, \rho(\omega), \Delta, \Lambda, \Sigma, \Xi, \Omega, J/\Psi$ and their antiparticles are considered in the calculations. An isospin averaged parametrization formula is used for the hh cross section [19, 20]. We also provide an option for the constant total, elastic, and inelastic cross sections ($\sigma_{tot}^{NN} = 40$ mb, $\sigma_{tot}^{\pi N} = 25$ mb, $\sigma_{tot}^{kN} = 35$ mb, $\sigma_{tot}^{\pi \pi} = 10$ mb) and the assumed ratio of inelastic to total cross section of 0.85. More details of hadronic rescattering can see [21].

III. CALCULATIONS AND RESULTS

In our calculations the default values given in the PYTHIA model are adopted for all model parameters except the parameters $K$ and $b_s$ (in the Lund string fragmentation function). $K=3$ is assumed and $b_s=6$ is tuned to the PHOBOS data of charged particle multiplicity in 0-6% most central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV [22], as shown in Tab. II.

In the theoretical calculation it is convenient to define the centrality by impact parameter $b_i$. The mapping relation between centrality definition in theory and experiment

$$b_i = \sqrt{b_i^m} = \sqrt{b_i^{R_A + R_B}}, \tag{6}$$

$$b_i^{R_A + R_B} = R_A + R_B.$$
TABLE I: Total charged particle multiplicity in three \( \eta \) fiducial ranges in 0-6\% most central Au+Au collisions at \( \sqrt{s_{NN}}=200 \) GeV.

| \( N_{ch}(|\eta| < 4.7) \) | \( N_{ch}(|\eta| < 5.4) \) | \( N_{ch}(\text{total}) \) |
|----------------|----------------|----------------|
| PHOBOS\(^a\) | 4810 ± 240 | 4960 ± 250 | 5060 ± 250 |
| PACIAE        | 4819         | 4983         | 5100         |

\(^a\) The experimental data are taken from [22].

is introduced [23]. In the above equation, \( g \) stands for the geometrical (total) cross section percentage (or charged multiplicity percentage) used in the experimental determination of centrality. \( R_A = 1.12A^{1/3} + 0.45 \) fm is the radius of nucleus \( A \). We have also used the centrality determination based on the charged multiplicity \( N_{ch} \) in the central pseudorapidity window \( |\eta| < 1 \) to study the FB multiplicity correlation strength as a function of \( \Delta \eta \).

FIG. 1: (Color online) The charged particle pseudorapidity distribution for the specified centrality bin in Au+Au collisions at \( \sqrt{s_{NN}}=200 \) GeV. The solid and open symbols are the PHOBOS data [22] and PACIAE results, respectively.

We compare the calculated charged particle pseudorapidity distribution in specified centrality bin in Au+Au collisions at \( \sqrt{s_{NN}}=200 \) GeV with the corresponding PHOBOS data [22] in Fig. 1. Here the theoretical centralities are defined by impact parameter \( b_i \) via Eq.(6). One sees that the PHOBOS data are well reproduced.

The PACIAE model results of FB multiplicity correlation strength are shown in Fig. 2 (a) and (b) for the centrality determinations of the impact parameter \( b_i \) and charged multiplicity \( N_{ch}(|\eta| < 1) \), respectively. One sees in Fig. 2 (a) that the theoretical results can reproduce the STAR data for 0-10\% most central collisions. However the theoretical results are all higher than the corresponding STAR data for the 10-20\%, 20-30\%, 30-40\%, and 40-50\% most central collisions and those theoretical results are closed to each other. That is because the FB multiplicity correlation in Au+Au collisions is mainly the statistical correlation stemming from the multiplicity fluctuation [14]. And the multiplicity fluctuation in those centralities defined by impact parameter are similar to each other.

Figure 2 (b) gives the FB correlation strength calculated with the charged particle multiplicity \( (|\eta| < 1) \) centrality determination together with the STAR data. We see in this panel that the STAR data are well reproduced by the PACIAE model for the 0-10\%, 10-20\%, and 20-30\% central collisions. However, the PACIAE results are higher than the corresponding STAR data for 30-40\%, and 40-50\% central collisions. The correlation strength approaches an exponential function of \( \Delta \eta \) observed by STAR in 40-50\% central collisions can not be reproduced especially.

In Fig. 3 we compare the FB multiplicity correlation strength as a function of \( \Delta \eta \) calculated by the wounded nucleon model [12], GMC code with a “toy” wounded-nucleon model, HSD transport approach [13], and PACIAE model with the STAR data for the 0-10\% (panel(a)) and 40-50\% central collisions (panel (b)). We see in Fig. 3 (a) that all of the four models can nearly
represents the STAR data for 40-50% central collisions, therefore it cannot reproduce $b$ as an exponential function of $\Delta \eta$ observed by STAR as shown in Fig. 3 (b).

We have noted the mentions in [6] that “To avoid a bias in the FB correlation measurements, care was taken to use different pseudorapidity selection for the centrality determination which is also based on multiplicity. Therefore, the centrality determination for the FB correlation strength for $\Delta \eta=0.2$, 0.4, and 0.6 is based on the multiplicity in $0.5 < |\eta| < 1.0$, while for $\Delta \eta=1.2$, 1.4, 1.6, and 1.8, the centrality is obtained from $|\eta| < 0.5$. For $\Delta \eta=0.8$ and 1.0, the sum of multiplicities from $|\eta| < 0.3$ and $0.8 < |\eta| < 1.0$ is used for the centrality determination.” So we follow STAR’s centrality determination convention to repeat all of the PACIAE calculations and draw Fig. 4 with these results. Comparing Fig. 4 with Fig. 2 (b) we see this complicated centrality determination does not improve but even worsens the agreement between experiment and theory. That means STAR’s centrality determination convention may be needed for the experimental measurement of FB correlation strength but not for the theoretical calculation.

In this kind of theoretical calculations, each definite centrality curve in Fig. 4 is composed of $b$ calculated at different $\Delta \eta$ with different centrality determination, such kind of curve is not reasonable in theoretical physics.

![FIG. 3: (Color online) The FB multiplicity correlation strength $b$ calculated by different models are compared with the STAR data for (a) 0-10% and (b) 40-50% central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV.](image)

![FIG. 4: (Color online) The same as Fig. 2 (b) but the PACIAE results are calculated with STAR’s convention of different centrality determination for different measured $\Delta \eta$ points (see text for the details.).](image)

![FIG. 5: (Color online) The PACIAE calculated FB multiplicity correlation strength $b$ in Pb+Pb collisions at $\sqrt{s_{NN}}=5500$ GeV with centrality determination of charged particle multiplicity $N_{ch}$ ($|\eta| < 1$).](image)
lisions is smaller than in Au+Au collisions. One reason may be that the multiplicity in Pb+Pb collisions at LHC energy is much larger than in Au+Au collisions at RHIC energy (the $N_{ch}/d\eta$ at mid-rapidity, $|\eta|<0.5$, is about 600 in 0-10% most central Au+Au collisions at RHIC energy but it is around 1200 in 0-10% most central Pb+Pb collisions at LHC energy [24]). This observation is similar to the report that the elliptic flow parameter $v_2$ in Pb+Pb collisions at LHC energy is significantly smaller than in Au+Au collisions at RHIC energy [25]. That is attributed to the fact that the hard process is more influential at the LHC energy than RHIC energy in [25]. Whether the competition between the hard and soft processes is also the reason of the FB multiplicity correlation decreasing from RHIC energy to LHC energy is beyond this paper scope, and it would be studied later.

**IV. CONCLUSION**

We have used a parton and hadron cascade model, PACIAE, to study the centrality dependence of charged particle FB multiplicity correlation strength in 0-10%, 10-20%, 20-30%, 30-40%, and 40-50% central Au+Au collisions at $\sqrt{S_{NN}}=200$ GeV. For the 0-10%, 10-20%, and 20-30% central collisions, the STAR data are well reproduced. The STAR observed characters of (1) $b$ as a function of $\Delta \eta$ is approximately flat for central collisions and (2) $b$ decreases with decreasing centrality are reproduced as well. However the PACIAE results are higher than the STAR data for the 30-40% and 40-50% central collisions and can not obtain $b$ as an exponential function of $\Delta \eta$ for the 40-50% central collisions, especially.

It turned out that the PACIAE model is somewhat better than the wounded nucleon model, the GEM code with a “toy” wounded-nucleon model, or the HSD transport model in comparing with the STAR correlation data. However all the models can not reproduce $b$ as an exponential function of $\Delta \eta$ in the 40-50% central collisions observed by STAR. That should be studied further.

The PACIAE calculations are repeated using the STAR’s centrality determination convention mentioned above. The results not improve but even worsens the agreement between theory and experiment. This means STAR’s centrality determination convention may be needed for the experimental measurement but not for the theoretical calculations. Because in such theoretical calculations, each definite centrality curve is composed of $b$ calculated at different $\Delta \eta$ with different centrality determination, this kind of curve is not reasonable in theoretical physics.

A prediction for the charged particle FB multiplicity correlation strength in 0-10% Pb+Pb collisions at $\sqrt{S_{NN}}=5500$ GeV is also given. The charged particle FB multiplicity correlation strength in Pb+Pb collisions at LHC energy is much smaller than in Au+Au collisions at RHIC energy. The further study is out of present paper scope and has to be investigated in another paper.

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[1] R. C. Hwa, Int. J. Mod. Phys. E 16, 3395 (2008).
[2] T. K. Nayak, J. of Phys. G 32, S187 (2006).
[3] J. Adams, et al., STAR Collaboration, Phys. Rev. C 75, 034901 (2007).
[4] A. Adare, et al., PHENIX Collaboration, Phys. Rev. Lett. 98, 232302 (2007).
[5] Zheng-Wei Chai, et al., PHOBOS Collaboration, J. of Phys.: Conference Series 27, 128 (2005).
[6] B. I. Abelev, STAR Collaboration, Phys. Rev. Lett. 103, 172301 (2009).
[7] N. S. Amelin, N. Armesto, M. A. Braun, E. G. Ferreiro, and C. Pajares, Phys. Rev. Lett. 73, 2813 (1994); N. Armesto, M. A. Braun, and C. Pajares, Phys. Rev. C 75, 054902 (2007).
[8] R. C. Hwa and C. B. Yang, arXiv:nucl-th/0705.3073.
[9] P. Brogueira, J. Dias de Deus, and J. G. Milhano, Phys. Rev. C 76, 064901 (2007).
[10] Yu-Liang Yan, Bao-Guo Dong, Dai-Mei Zhou, Xiao-Mei Li, Hai-Liang Ma, and Ben-Hao Sa, Phys. Rev. C 79, 054902 (2009).
[11] A. Capella, U. Sukhatme, C.-I. Tan, and J. Tran Thanh Van, Phys. Rep. 236, 225 (1994).
[12] Dai-Mei Zhou, Xiao-Mei Li, Bao-Guo Dong, and Ben-Hao Sa, Phys. Lett. B 638, 461 (2006); Ben-Hao Sa, Xiao-Mei Li, Shou-Yang Hu, Shou-Ping Li, Jing Feng, and Dai-Mei Zhou, Phys. Rev. C 75, 054912 (2007).
[13] T. Söjstrand, S. Mrenna, and P. Skands, J. High Energy Phys. JHEP05, 026 (2006).
[14] B. L. Combridge, J. Kripfgang, and J. Ranft, Phys. Lett. B 70, 34 (1977).
[15] P. Koch, B. Müller, and J. Rafelski Phys. Rep. 142, 167 (1986).
[16] A. Baldini, et al., “Total cross sections for reactions of high energy particles”, Springer-Verlag, Berlin, 1988.
[17] Ben-Hao Sa and Tai An, Comput. Phys. Commun. 90, 121 (1995); Tai An and Ben-Hao Sa, Comput. Phys. Commun. 116, 353 (1999).
[18] B. B. Back, et al., PHOBOS Collaboration, Phys. Rev. Lett. 91, 052303 (2003).
[19] Ben-Hao Sa, A. Bonasera, An Tai and Dai-Mei Zhou, Phys. Lett. B 537, 268 (2002).
[24] Ben-Hao Sa, Dai-Mei Zhou, Bao-Guo Dong, Yu-Liang Yan, Hai-Liang Ma, and Xiao-Mei Li, J. Phys. G 36, 025007 (2009).
[25] G. Eyyubova, L. V. Bravina, E. Zabrodin, V. L. Kotrotkikh, I. P. Lokhtin, L. V. Malinina, S. V. Petrushanko, and A. M. Snigirev, Phys. Rev. C 80, 064907 (2009).