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Event-by-event analysis of baryon-strangeness correlations: Pinning down the critical temperature and volume of quark-gluon-plasma formation

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The recently proposed baryon-strangeness correlation ($C_{\rm BS}$) is studied with a string-hadronic transport model (UrQMD) for various energies from $E_{\rm lab} = 4A$ GeV to $\sqrt{s} = 200A$ GeV. It is shown that rescattering among secondaries cannot mimic the predicted correlation pattern expected for a quark-gluon-plasma. However, we find a strong increase of the $C_{\rm BS}$ correlation function with decreasing collision energy for $p+p$ and Au+Au and/or Pb+Pb reactions. For Au+Au reactions at the top BNL Relativistic Heavy Ion Collider energy ($\sqrt{s} = 200A$ GeV), the $C_{\rm BS}$ correlation is constant for all centralities and compatible with the $p+p$ result. With increasing width of the rapidity window, $C_{\rm BS}$ follows roughly the shape of the baryon rapidity distribution. We suggest studying the energy and centrality dependence of $C_{\rm BS}$ to gain information on the onset of the deconfinement transition in temperature and volume.

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Several observables [1] have been proposed throughout the Past few decades to study the characteristics of the highly excited matter created in heavy ions collisions, where a quark-gluon-plasma (QGP) is believed to be created. Among these observables that provide the opportunity to probe whether the system went through a phase of deconfined quarks and gluons, the ones related to fluctuations and correlations seem to be the most promising. Fluctuation probes might be more adequate for the exploration of heavy-ion reactions, because the distributions of energy density or initial temperature, isospin and particle density have strong fluctuations from event to event [2–4]. On the theoretical side, event-by-event fluctuations were suggested to study the following:

(i) kinetic and chemical equilibration in nuclear collisions [5–14],
(ii) the onset of the deconfinement phase [15–21]
(iii) the location of the tri-critical end point of the quantum chromodynamics (QCD) phase transition [22–24] or
(iv) the formation of exotic states, such as disoriented chiral condensates (DCC) [25].

On the experimental side, progress has been made by many experiments to extract momentum and particle number ratio fluctuations from heavy-ion reaction: E-by-E fluctuations are actively studied in the SPS energy regime (starting from 20A GeV on) by the NA49 group [26–34] and the CERES Collaboration [35–38]. At RHIC energies the PHENIX [39–41] and STAR [42–44] experiments are addressing the field of single event physics.

Recently a novel event-by-event observable has been introduced by Koch *et al.* [45]; the baryon-strangeness correlation coefficient $C_{\rm BS}$. This correlation is proposed as a tool to specify the nature (ideal QGP or strongly coupled QGP or hadronic matter) of the highly compressed and heated matter created in heavy-ion collisions. The idea is that depending on the phase the system is in, the relation between baryon number and strangeness will be different: On the one hand, if one considers an ideal plasma of quarks and gluons, strangeness will be carried by freely moving strange and antistrange quarks, carrying baryon number in strict proportions. This leads to a strong correlation between the baryon number and strangeness. On the other hand, if the degrees of freedom are of hadronic nature, this correlation is different, because it is possible to carry strangeness without baryon number, e.g., in mesons or QGP bound states.

To quantify to what degree strangeness and baryon number are correlated, the following correlation coefficient has been proposed [45]:

$$C_{\rm BS} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2}, \tag{1}$$

where B is the baryon charge and S is the strangeness. If a QGP is created, the expected value of $C_{\rm BS}$ will be unity as expected from lattice QCD, compatible with the ideal weakly coupled QGP. In the case of a hadron gas, where the correlation is nontrivial, this quantity has been evaluated in Ref. [45] to be $C_{\rm BS} = 0.66$.

In this article, we study the correlation coefficient $C_{\rm BS}$ with the ultrarelativistic quantum molecular dynamics model (UrQMD v2.2). The UrQMD is a nonequilibrium microscopic transport model that simulates the full space-time evolution of heavy-ion collisions. It is valid from a few tens of megaelectron volts to several teraelectron volts per nucleons in the laboratory frame. It describes the rescattering of incoming and produced particles, the excitation and fragmentation of color strings and the formation and decay of resonances. This model has been used before to study event-by-event fluctuations rather successfully [4,7,16,21,25] and yields a reasonable description of inclusive particle distributions. For a complete review of the model, the reader is referred to [46,47].

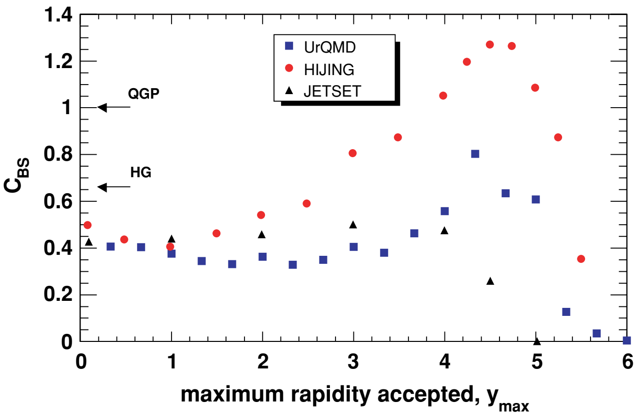

FIG. 1. (Color online) Correlation coefficient for central Au+Au collisions at $\sqrt{s} = 200$ shown as a function of the maximum rapidity accepted. Circles are the calculation with HIJING [49]. Squares are the result of the UrQMD calculation and triangles of the JETSET for e^+e^- at $\sqrt{s} = 200$. The arrows are the values of a quark gluon plasma and of an hadron gas at a temperature $T = 170$ and chemical potential $\mu_B = 0$ [45]. Both HIJING and JETSET results are taken from Ref. [45].

Because the UrQMD is based on hadrons and strings it provides an estimate of the C_{BS} value in the case where no QGP is created; however, taking into account the rescattering and the nonequilibrium nature of the heavy-ion reactions. C_{BS} is evaluated from the event-by-event fluctuation analyses following [45,48]:

$$C_{BS} = -3\frac{\frac{1}{N}\sum_n B^{(n)}S^{(n)} - \left(\frac{1}{N}\sum_n B^{(n)}\right)\left(\frac{1}{N}\sum_n S^{(n)}\right)}{\frac{1}{N}\sum_n (S^{(n)})^2 - \left(\frac{1}{N}\sum_n S^{(n)}\right)^2}, \quad (2)$$

$B^{(n)}$ and $S^{(n)}$ stand for the baryon number and strangeness in a given event n.

The correlation coefficient C_{BS} is depicted in Fig. 1 as a function of the maximum rapidity accepted ($|y| \leqslant y_{max}$). The analyzed sample consists of central Au+Au events at $\sqrt{s} = 200A$ GeV. For small acceptance windows around midrapidity, C_{BS} stays roughly constant. Although for a large acceptance window, C_{BS} increases because of the inclusion of the fragmentation region with high baryon density. The different models deviate from each other for large acceptances because of differences in the handling of the fragmentation region, with small rapidity acceptance (relevant for the RHIC experiments); HIJING, JETSET, and UrQMD yield consistent results. It should be noted that all discussed models deviate from the hadronic gas expectations; this is to be expected, because of nonequilibrium effects and an underprediction of multistrange baryons compared to statistical models. If the window acceptance covers all produced particles, C_{BS} has to vanish because of baryon number conservation.

In case a QGP is created, the signal given by the C_{BS} coefficient should survive the hadronic phase. With a strong enough longitudinal flow, strangeness and baryon number within a given rapidity range should be frozen in. The used rapidity window cannot be too wide to avoid global baryon number and strangeness conservation. Nevertheless, the acceptance window must be wide enough to avoid smearing because of hadronization.

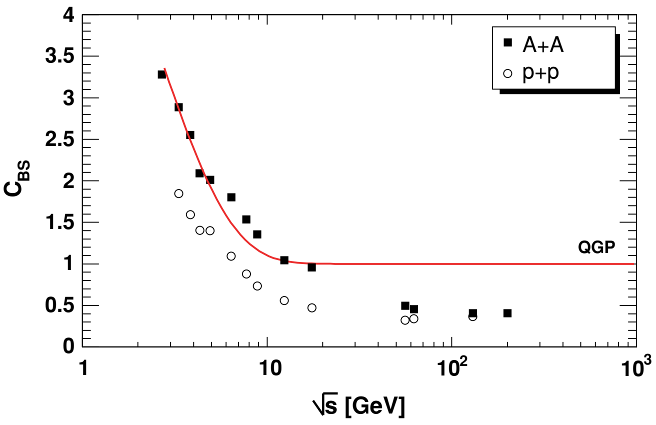

FIG. 2. (Color online) Correlation coefficient C_{BS} for central Au+Au and/or Pb+Pb (full symbols) and minimum bias $p+p$ collisions (open symbols) as a function of $\sqrt{s}$. The maximum rapidity accepted is $y_{max} = 0.5$. The line indicates the expected behavior if a QGP is formed.

Figure 2 depicts the energy excitation function of C_{BS} in both $p+p$ and centrals Au+Au/Pb+Pb collisions. As discussed in Ref. [45], C_{BS} increases with an increase of the baryon chemical potential μ_B when going to lower beam energies. With increasing collision energy, and therefore decreasing μ_B, C_{BS} goes down to $C_{BS} \approx 0.4$ at the highest RHIC energy available. Surprisingly, the general trend is the same for both $p+p$ and Au+Au and/or Pb+Pb. To show the expected behavior for a transition to a QGP around 30A GeV, we have extrapolated the QCD results to lower energies and matched them with the hadronic gas results (shown as line). Thus, measuring the energy dependence of C_{BS} correlation around midrapidity might therefore allow to map out the onset of the QGP production.

The dependence of C_{BS} on the number participants is studied in Fig. 3. The number of participants is determined via

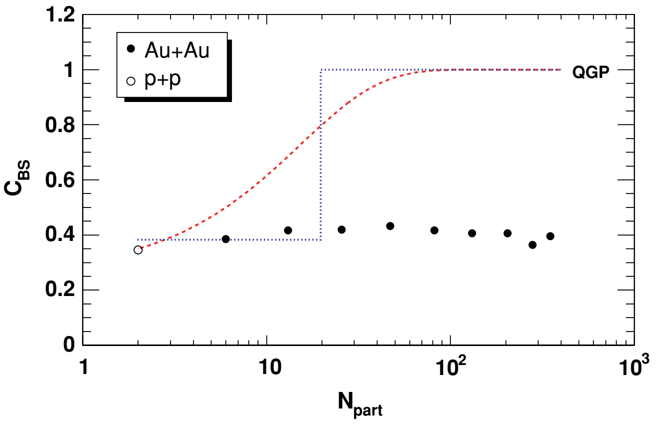

FIG. 3. (Color online) Correlation coefficient for Au+Au collisions at $\sqrt{s} = 200$ as a function of the number of participants. The maximum rapidity accepted is $y_{max} = 0.5$. Full symbols are the results for Au+Au and the open symbol shows the $p+p$ value. The lines indicate the expected behavior if a QGP is formed (see text for details).

the scaled number of π^-s in 4π geometry ($N_{\rm part} = 0.2\langle\pi^-\rangle$). This quantity is proportional to the overlap volume of the colliding nuclei and thus to the number of participants. The UrQMD model predicts a flat dependence of $C_{\rm BS}$ on centrality. $C_{\rm BS} \approx 0.4$ from $p+p$ to central Au+Au events. This is in strong contrast with what is to be expected if the system enters a QGP phase at some centrality. In this case $C_{\rm BS}$ will increase from peripheral AA or *pp* toward central AA collisions. To illustrate the expected change with centrality in case of a QGP, Fig. 3 shows two QGP scenarios that assume a transition to a QGP at around 30 participant nucleons (indicated as lines)—whether this transition is smooth (dashed line) or as a step function (dotted line) depends on the onset behavior of the QGP phase. This might allow to extract in detail the volume dependence of the deconfinement transition at RHIC.

To summarize, we have studied the dependence of the baryon-strangeness correlation coefficient as a function of the center-of-mass energy from $E_{\rm lab} = 4A$ GeV to $\sqrt{s} = 200A$ GeV for $p+p$ and central Au+Au and/or Pb+Pb reactions. At $\sqrt{s} = 200A$ GeV we have explored the centrality dependence of the $C_{\rm BS}$ correlation. $C_{\rm BS}$ is found to decrease from the lower energies toward the top RHIC energy available (here $C_{\rm BS} \approx 0.4$). For minimum bias Au+Au events at $\sqrt{s} = 200$, we predict a flat centrality dependence of $C_{\rm BS}$ near midrapidity. At the highest RHIC energy the $C_{\rm BS}$ value from the microscopic transport model is roughly half the one expected in the case of a QGP. We suggest to study the energy and centrality dependence of $C_{\rm BS}$ which allow to gain information on the onset of the deconfinement transition in temperature and volume. The CERES/NA49 and STAR experiments should be able to perform these analysis with their accumulated data.

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