Baseline measures for net-proton distributions in high energy heavy-ion collisions

P. K. Netrakanti, X. F. Luo, D. K. Mishra, B. Mohanty, A. Mohanty and N. Xu

1 Nuclear Physics Division, Bhabha Atomic Research Center, Mumbai 400094, India, 2 Key Laboratory of the Ministry of Education of China, Central China Normal University, Wuhan, 430079, China, 3 School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar-751005, India, and 4 Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

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We report a systematic comparison of the recently measured cumulants of the net-proton distributions for 0-5% central Au+Au collisions in the first phase of the Beam Energy Scan (BES) Program at the Relativistic Heavy Collider facility to various kinds of possible baseline measures. These baseline measures correspond to assuming that the proton and anti-proton distributions follow Poisson statistics, Binomial statistics, obtained from a transport model calculation and from a hadron resonance gas model. The higher order cumulant net-proton data corresponding to the center of mass energies (\(\sqrt{s_{NN}}\)) of 19.6 and 27 GeV are observed to deviate from all the baseline measures studied. The deviations are predominantly due to the difference in shape of the proton distributions between data and those obtained in the baseline measures. We also present a detailed study on the relevance of the independent production approach as a baseline for comparison with the measurements at various beam energies. Our studies point to the need for a proper comparison of the experimental measurements to QCD calculations in order to extract the exact physics process that leads to deviation of the data from the baselines presented.

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I. INTRODUCTION

The STAR experiment at the Relativistic Heavy Ion Collider facility has recently reported interesting results on the shape of the net-proton distributions at various collision energies [1]. These measurements are carried out as a part of the first phase of the beam energy scan program to look for the signatures of the possible critical point (CP) in the phase diagram for a system undertaking strong interactions. The shape of the net-proton distributions (a proxy for net-baryon distributions) is quantified in terms of the cumulants of the distribution. Measurements up to the fourth order cumulants (\(C_n, n = 1, 2, 3, 4\)) has been reported as a function of the colliding beam energy. Varying the beam energy of the collision also varies the baryon chemical potential of the system. Thereby allowing experimentally to scan the temperature versus baryon chemical potential phase diagram of strong interactions. The STAR experiment has reported an intriguing dependence of the cumulant ratios \(C_3/C_2\) and \(C_4/C_2\) as a function of beam energy. The beam energy dependence appears to be non-monotonic in nature. However the experiment also reports that the energy dependence is observed to be consistent with expectation from an approach based on the independent production of proton and anti-protons in the collisions [1].

In this paper we first establish that at the lower colliding energies the beam energy dependence of the net-proton cumulant ratios are dominantly due to the corresponding proton distributions. Very much similar to recently reported, non-monotonic beam energy dependence of the slope of the net-proton directed flow at midrapidity being dominantly due to the corresponding contribution from the measured proton directed flow [2]. We emphasize the need to have a proper baseline for appropriate interpretation of the cumulant measurements and argue that the comparison to independent production approach needs to be done with extreme caution. We demonstrate through our study that the applicability of the independent production approach at lower beam energies where the anti-proton production is very small is questionable. Further, we have argued that the agreement at the higher beam energies in spite of significant correlated production of proton and anti-proton (\(p/\bar{p} \sim 0.77\), for 0-5% central Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV [3]) in the collisions could be a coincidence due to the acceptance in which measurements have been carried out. In addition we point out the role of particle production mechanism and baryon number conservation to such approaches. We have also carried out a very systematic comparison of the four measured cumulants to a variety of baselines measures. These include, expectations if proton and anti-proton distributions are Poisson, Binomial, those obtained from a transport model and from a hadron resonance gas (HRG) Model. All these variety of baselines indicate the higher order cumulant data deviates from them for central 0-5% Au+Au collisions at \(\sqrt{s_{NN}} = 19.6\) and 27 GeV.
The paper is organized as follows. Next section deals with the experimental data and sets up the physics problem addressed in the paper. Section III compares the cumulants measured in the experiment to the four different baseline measures. Section IV discusses in detail the independent production approach and finally in section V we summarize our findings.

II. EXPERIMENTAL DATA

Figure 1 shows the four cumulants of the measured proton, anti-proton and net-proton distributions at midrapidity in 0-5% central Au+Au collisions at RHIC BES program [1]. Also shown are the expectations from independent production model.

FIG. 1: Cumulants of proton, anti-proton and net-proton multiplicity distribution at midrapidity in 0-5% central Au+Au collisions at RHIC BES program [1].

The experimental data on cumulants of net-proton distribution are taken and corresponding cumulants for net-proton distribution constructed assuming that proton and anti-proton productions are independent of each other. They are expected to have errors of the same order as data by construction. For the IP, the various order (n = 1, 2, 3 and 4) net-proton cumulants are given as $C_n = C_{n}^{p} + (-1)^{n} C_{n}^{\bar{p}}$, where $C_{n}^{p}$ and $C_{n}^{\bar{p}}$ are the cumulants of the measured proton and anti-proton distributions. IP results seem to explain the experimentally measured net-proton cumulants for all beam energies. However, for $\sqrt{s_{NN}}$ < 39 GeV, the IP model applicability is questionable as the net-proton cumulants are dominated by contributions from protons only. Hence due to the absence of significant anti-proton production, the basic assumption in IP model that proton and anti-proton productions are independent is not applicable and proton distributions solely reflect the net-proton distributions. At the same time it is known from the measured $\bar{p}/p$ ratio (~ 0.77 at midrapidity in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [3]) there is a significant level of correlation between proton and anti-proton production. Hence the agreement of IP model results at the higher side of the beam energies studied is also intriguing. Further, the role of baryon number conservation on such an approach has to be understood properly. Understanding of the IP model is attempted in the discussions using various models in section IV. All these also necessitates a discussion on other proper baselines for the experimental data, this is carried out in the section below.

III. BASELINE FOR CUMULANTS OF NET-PROTON DISTRIBUTION

A. Poisson

Poisson distribution represents a statistically random expectation of the observable. Taking the measured mean value of the number of protons and anti-protons produced in the heavy-ion collisions one can construct the corresponding net-proton distribution. The proton and anti-proton production are assumed to be independent. The resultant distribution is called the Skellam distribution. Figure 2 shows the comparison of the measured cumulants for proton, anti-proton and net-proton distributions to Poisson expectation. As the measured $C_1$ is used to construct the Poisson expectation the agreement is by construction. However Figure 2 shows as the order of cumulant increases we find deviations of the data from the Poisson expectation for protons and net-protons increases for $\sqrt{s_{NN}} < 62.4$ GeV. The anti-proton cumulants are reasonably well explained
by the Poisson expectation. Hence we conclude that data shows deviation from what is expected from a fully uncorrelated and random statistical process for the proton distributions and hence the same is reflected for the net-proton distributions for $\sqrt{s_{NN}} < 62.4$ GeV.

**B. Binomial**

Figure 3 shows the comparison of the measured cumulants for proton, anti-proton and net-proton 0-5% central collision distributions to Binomial expectation. To construct the binomial distributions, the measured $C_1$ and $C_2$ values of the proton and anti-proton distributions are taken. To obtain the corresponding distribution for net-proton, it is assumed that the binomially distributed proton and anti-proton are produced independently. Hence we see good agreement between data and binomial expectation for $C_1$ and $C_2$. Deviations are observed only for $C_4$ of the measured proton and hence net-proton distributions for $\sqrt{s_{NN}} = 19.6$ and 27 GeV. The cumulants of the anti-proton distribution like in the above case of Poisson expectation seems to also follow reasonably well the binomial expectation for all beam energies measured. Hence we conclude that the highest order measured cumulant for proton and net-proton distribution shows deviation from binomial expectation for $\sqrt{s_{NN}} = 19.6$ and 27 GeV. The difference between the Poisson expectation and binomial expectation comparison is that $C_3$ is reasonably well explained by binomial expectation unlike for the Poisson case. In turn for construction of binomial distribution we make use of both measured $C_1$ and $C_2$ of proton and anti-proton distributions while only $C_1$ is used to construct the corresponding distribution following Poisson statistics. A comparison of HIJING simulation results of $C_3/C_2$ and $C_4/C_2$ with the binomial and negative binomial distribution expectation are discussed in ref [4].

**C. Transport Model**

A transport based model, Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model [5] is expected to be effective in explaining several bulk observables at lower colliding energies. It is based on a microscopic transport theory where the phase space description of the reactions are important. It allows for the propagation of all hadrons on classical trajectories in combination with stochastic binary scattering, color string formation and resonance decay. It incorporates baryon-baryon, meson-baryon and meson-meson interactions, the collisional term includes more than 50 baryon species and 45 meson species. Figure 4 shows the comparison of the measured cumulants for proton, anti-proton and net-proton 0-5% central distributions to the corresponding results from UrQMD calculations obtained within the same acceptance as the experimental data [6]. The UrQMD model results are reasonably close to the experimentally measured $C_1$ and $C_2$ cumulants for proton, anti-proton and net-proton distributions. However there is clear devia-
tion from the experimentally measured higher order cumulants of proton and net-proton distributions for \( \sqrt{s_{NN}} = 19.6 \) and 27 GeV. The anti-proton distributions follow reasonably well the UrQMD expectations. Hence we conclude like for the case of Poisson and Binomial baseline measures the UrQMD model results for higher order cumulants cannot explain the measured values at \( \sqrt{s_{NN}} = 19.6 \) and 27 GeV.

D. Hadron Resonance Gas

Thermal model calculations including hadrons and its resonances are able to explain the yields of various hadrons produced in high energy heavy-ion collisions [7]. Here we compare the ratio of various measured cumulants of the proton, anti-proton and net-proton distributions for central 0-5% Au+Au collisions at various beam energies to a hadron resonance gas model calculation [8]. The calculation is performed for the same acceptance as the experimental data. The ratio of cumulants are taken to cancel out the volume effect to first order in such a model calculation. Figure 4 shows the comparison between data and HRG values for \( C_2/C_1 \), \( C_3/C_2 \), and \( C_4/C_2 \). The \( C_2/C_1 \) ratio is reasonably well explained for all the three (proton, anti-proton and net-proton) distributions for all energies. \( C_3/C_2 \) and \( C_4/C_2 \) ratios from anti-protons are reasonably well explained by HRG model. However the measured proton and net-proton \( C_3/C_2 \) and \( C_4/C_2 \) ratios shows clear deviation from HRG model values for \( \sqrt{s_{NN}} = 19.6 \) and 27 GeV.

We find that all the four baseline considered for understanding the experimental data on cumulants of measured proton, anti-proton and net-proton distributions are consistent with the finding that the 0-5% central Au+Au collision data at midrapidity for \( \sqrt{s_{NN}} = 19.6 \) and 27 GeV deviates from all them. This indicates data has evidence for new physics process not included or expected from the baseline measures considered.

IV. UNDERSTANDING INDEPENDENT PRODUCTION MODEL

In section II we have discussed why IP model explains the experimental data on cumulants of net-proton distributions for \( \sqrt{s_{NN}} < 39 \) GeV. It is essentially due to the fact (as shown in the Fig. 1) that the cumulants of net-proton distributions are dominantly determined from the cumulants of the corresponding proton distribution. However the puzzle still remains that in spite of significant correlated production of proton and anti-protons at high
energies, why the measured cumulants follow so closely the IP model. This aspect is discussed below using Heavy Ion Jet Interaction Generator (HIJING) model [9]. HIJING is an event generator for heavy-ion collisions. It is a perturbative QCD inspired model which produces multiple minijet partons, these later get transformed into string configurations and then fragment to hadrons. In addition the role of baryon number conservation on such an IP model as discussed in Ref [10] is also discussed.

A. Rapidity and Energy Dependence

Figure 6 shows the cumulants of proton, anti-proton and event-by-event (E-by-E) net-proton distribution from HIJING model in Au+Au collisions for 0-5% central collisions as a function of pseudorapidity (\(\eta\)) acceptance. The results are shown for two extreme beam energies (7.7 and 200 GeV) at RHIC for which data has been collected in Au+Au collisions. All cumulants increases with \(\eta\) acceptance upto the corresponding beam rapidity and then the values saturates for both \(\sqrt{s_{NN}} = 7.7\) and 200 GeV. There is hardly any anti-protons produced at 7.7 GeV collisions, hence the net-proton cumulants are dominated by the corresponding cumulants of the proton distribution. Therefore the IP model expectation very closely follows the net-proton and proton cumulant values. Therefore the IP model should not be considered as a baseline for the lower beam energies. In contrast we see interesting \(\eta\) dependence for the Au+Au collisions simulated in HIJING at 200 GeV. A considerable amount of anti-protons are produced and we find the net-proton \(C_1\) and \(C_3\) closely agree with IP expectation for the full \(\eta\) range studied. However we see clear deviation of net-proton \(C_2\) and \(C_4\) from the corresponding IP expectation for \(\eta > 0.5\). This study suggests that the agreement between data and corresponding IP result is because of the \(\eta\) acceptance of the measurement and larger acceptance would perhaps have shown the deviations. The deviations are as expected from the breaking of the correlations due to the proton and anti-proton pair production in IP construction at high beam energies.

B. THERMINATOR

In this subsection we investigate another possibility of agreement between IP expectation and data at higher beam energies. We consider THERMINATOR event generator [11], which produces particles assuming thermal equilibrium, grand canonical ensemble and ideal hydrodynamics.


FIG. 7: Cumulants of proton, anti-proton and net-proton multiplicity distribution as a function of number of participating nuclei in Au+Au collisions from THERMINATOR [11] at $\sqrt{s_{NN}} = 200$ GeV. Also shown is the expectation for net-proton from Independent Production (IP) model. The top panel is for the $p_T$ range from 0.4 to 0.8 GeV/c and $|\eta| < 0.5$, while the bottom panel is for $p_T > 0$ and $|\eta| < 6.0$.

C. Baryon Number Conservation

The net-baryon number probability distribution for both baryon and anti-baryon distributions following Poisson distribution and with baryon number conservation is given as [10]:

$$P_B(n) = \left(\frac{p_B}{\bar{p}_B}\right)^{n/2} \left(\frac{1-p_B}{1-\bar{p}_B}\right)^{(B-n)/2}$$

$$\times I_n\left(2z\sqrt{p_B\bar{p}_B}\right) I_{B-n}\left(2z\sqrt{(1-p_B)(1-\bar{p}_B)}\right),$$

where $z = \sqrt{\langle N_B \rangle / \langle N_B \rangle}$, $\langle N_B \rangle$ is the average number of baryons, $\langle N_{-B} \rangle$ is the average number of anti-baryons and $I_n$ is the modified Bessel function of first kind. The analogous equation for net-proton is obtained from Eqn.1 by [10]

$$p_B = \frac{\langle n_B \rangle}{\langle N_B \rangle} \rightarrow \frac{\langle n_p \rangle}{\langle N_B \rangle},$$

where $\langle n_p \rangle$ is the mean number of observed protons and analogously for anti-protons.

Since it involves the knowledge of average number of total baryons and anti-baryons produced in the collisions, we tested the comparison of IP with and without baryon number conservation (BNC) in HIJING model. Figure 8 shows the ratio of cumulants of net-proton distributions in 10-15% collision centrality for Au+Au collisions in HIJING for various beam energies. This result is compared to expectation from IP approach without baryon number conservation and with baryon number conservation (denoted as BNC). While not much difference is observed for the three cases for the ratio $C_2/C_1$, differences between IP and BNC starts to show for higher order ratios of $C_3/C_2$ and $C_4/C_2$ at higher beam energies. This also emphasizes the need to properly construct the IP approach considering the effect of baryon number conservation while comparing to the experimental data.

We have discussed in this section that IP approach needs to carefully used as a baseline for comparison to data. Applicability of IP approach at lower beam energies where shape of the net-proton distribution is dominated by those from protons only is questionable. At higher beam energies similarity between IP and data could be a coincidence due to small acceptance. The importance of implementing the baryon number conservation effect is emphasized. Further we find the IP approach is also sensitive to the mechanism of particle production, as one based on thermal model and ideal hydrodynamics as in THERMINATOR gives a different conclusion to that based on HIJING.
FIG. 8: Ratio of cumulants of net-proton multiplicity distribution as a function of beam energy in Au+Au collisions from HIJING. Also shown are the expectations for net-proton cumulant ratios from corresponding Independent Production approach with (BNC) and without (IP) baryon number conservation incorporated.

V. SUMMARY

In summary, we have discussed several possible baseline measures for understanding the net-proton cumulants measured in STAR experiment at RHIC. The data tends to show a non-monotonic variation in the higher order ratios of cumulants as a function of beam energy. The baseline measures considered are those where the underlying proton and anti-proton distributions are Poisson, binomial, those generated from a transport model and a hadron resonance gas model. Results from all baseline measures studied indicate that higher order cumulants for 0-5% Au+Au collision data deviates from them at $\sqrt{s_{NN}} = 19.6$ and 27 GeV. This indicates presence of new physics, which could be related to a critical point in the strong interaction phase diagram. A high statistics measurement at lower beam energies as planned in the second phase of the RHIC beam energy scan program and a detailed comparison to QCD calculations with critical point will be able to settle the physics picture.

We have discussed several drawbacks of comparing the data to a simple IP approach. At lower beam energies the comparison is not valid as the net-proton distribution are dominated by the shape of the proton distribution only. This arises due to small yields of anti-protons at the lower beam energies. Further at higher beam energies the agreement between data and IP could be mere coincidence due to the acceptance range used in the measurement. This aspect we have demonstrated using a simulation study based on HIJING model. We have also pointed out through the HIJING simulations that such IP approach also needs to incorporate baryon number conservation effects. This is true for all baseline measurements. Finally we have also shown that the agreement between IP and the data could also depend on the mechanism of particle production. In an event generator like THERMINATOR that assumes particle production from a thermalized source shows no difference between the model cumulant results and the corresponding IP result.

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