

## Beam energy dependence of net- $\Lambda$ fluctuations measured by the STAR experiment at the BNL Relativistic Heavy Ion Collider

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The measurements of particle multiplicity distributions have generated considerable interest in understanding the fluctuations of conserved quantum numbers in the quantum chromodynamics (QCD) hadronization regime, in particular near a possible critical point and near the chemical freeze-out. Net-protons and net-kaons have been used as proxies for the net-baryon number and net-strangeness, respectively. We report the measurement of efficiency- and centrality-bin width-corrected cumulant ratios ( $C_2/C_1$ ,  $C_3/C_2$ ) of net- $\Lambda$  distributions, in the

context of both strangeness and baryon number conservation, as a function of collision energy, centrality, and rapidity. The results are for Au + Au collisions at five beam energies ( $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4, \text{ and } 200 \text{ GeV}$ ) recorded with the Solenoidal Tracker at RHIC (STAR). We compare our results to the Poisson and negative binomial (NBD) expectations, as well as to ultrarelativistic quantum molecular dynamics (UrQMD) and hadron resonance gas (HRG) model predictions. Both NBD and Poisson baselines agree with data within the statistical and systematic uncertainties. UrQMD describes the measured net- $\Lambda$   $C_1$  and  $C_3$  at 200 GeV reasonably well but deviates from  $C_2$ , and the deviation increases as a function of collision energy. The ratios of the measured cumulants show no features of critical fluctuations. The chemical freeze-out temperatures extracted from a recent HRG calculation, which was successfully used to describe the net-proton, net-kaon, and net-charge data, indicate  $\Lambda$  freeze-out conditions similar to those of kaons. However, large deviations are found when comparing with temperatures obtained from net-proton fluctuations. The net- $\Lambda$  cumulants show a weak but finite dependence on the rapidity coverage in the acceptance of the detector, which can be attributed to quantum number conservation.

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## I. INTRODUCTION

Relativistic heavy-ion collisions provide significant information on the nuclear matter phase transition under extreme temperatures and energy densities. The Beam Energy Scan (BES) program at the Relativistic Heavy Ion Collider (RHIC) was established for the purpose of studying the QCD phase diagram as a function of temperature  $T$  and baryon chemical potential  $\mu_B$ . Lattice QCD calculations suggest that the phase transition from quark gluon plasma (QGP) to hadron gas at low  $\mu_B$  is a smooth crossover [1], while at relatively high  $\mu_B$  effective chiral theories predict a first-order transition [2,3]. Probing the existence of an endpoint for the first-order phase transition, i.e., the QCD critical point, and mapping the chemical freeze-out process of hadrons at different  $T$  and  $\mu_B$  are two major goals of the fluctuation measurements in the BES program at RHIC.

Fluctuations of conserved quantum numbers, in particular charge  $Q$ , baryon number  $B$ , and strangeness  $s$ , show sensitivity to the QCD phase transition [4–6]. These quantum numbers can be represented by experimentally measured net-particle multiplicities [7]. Potential proxies for the net-charge  $\Delta Q$ , net-baryon number  $\Delta B$ , and the net-strangeness  $\Delta s$  are the net-charged particle, net-proton, and the net-kaon multiplicities, respectively. Each proxy has unique caveats in fully reflecting the behavior of the conserved quantum number during the transition. Thus, in this paper we exclusively use comparisons to phenomenological approaches, such as ultrarelativistic quantum molecular dynamics (UrQMD) and hadron resonance gas (HRG), which can model these caveats when describing the experimental results, rather than compare directly to lattice QCD calculations. Moments of net-particle multiplicity distributions such as mean  $M$ , standard deviation  $\sigma$ , skewness  $S$ , and kurtosis  $\kappa$  are related to the thermodynamic susceptibilities  $\chi_i^{(n)}$ , where  $n$  is the order of the susceptibility and  $i$  stands for the type of conserved quantum number. These susceptibilities can also be written in terms of cumulants  $C_n$  as  $\chi_i^{(n)} = (1/V T^3) C_n$ , where  $V$  and  $T$  stand for volume and temperature, respectively [8]. Moment products or ratios of net-particle multiplicity distributions are related to the volume-independent susceptibility ratios as  $\sigma^2/M = \chi_i^{(2)}/\chi_i^{(1)}$  and  $S\sigma = \chi_i^{(3)}/\chi_i^{(2)}$ . Thermodynamic susceptibilities have been modeled in lattice QCD at  $\mu_B = 0$  [8–15] and

in HRG models at finite  $\mu_B$  [16–19] as a function of  $T$  and  $\mu_B$ . By comparing the experimentally measured fluctuations of net-particle multiplicity distributions with the theoretically calculated quantum number susceptibilities at different collision energies, the freeze-out temperature of the strongly interacting matter can be determined for different chemical potentials. In this context, the net-kaon fluctuation measurements have been studied as a proxy for net-strangeness, and the net-proton results were used to study net-baryon number [20,21]. The freeze-out temperatures extracted by comparing the latest HRG model calculations with STAR net-kaon fluctuation measurements revealed higher values than the freeze-out temperatures extracted from previous measurements by STAR of the net-charge and net-proton fluctuations [22].

The  $\Lambda$  carries both baryon and strangeness quantum number. Thus, the study of the event-by-event net- $\Lambda$  ( $\Lambda$  multiplicity –  $\bar{\Lambda}$  multiplicity) fluctuations is important for the understanding of the freeze-out temperature in the context of both baryon number and strangeness conservation. Predicted sequential hadronization [23] can be addressed by comparing the net- $\Lambda$  fluctuations with the latest HRG results [22], which calculate the cumulant ratios using the freeze-out conditions from different fluctuation measurements of net-quantum numbers. Additionally, net- $\Lambda$ s paired with net-kaons provide a more complete measurement of the net-strangeness fluctuations, while paired with net-protons the results are closer to a complete measurement of the fluctuations of the net-baryon number. Net- $\Lambda$  fluctuations are also the main contribution to the measurement of the off-diagonal baryon-strangeness correlator, and thus add to recent STAR and theoretical publications on this issue [24–26].

In this paper, the first measurements of the net- $\Lambda$  fluctuations in Au + Au collisions using the STAR (solenoidal tracker at RHIC) experiment are presented as a function of collision energy, centrality, and rapidity. Results are compared with the Poisson and negative binomial distribution (NBD) baselines, as well as with the UrQMD predictions [27] and the predictions from the latest HRG model [22].

## II. ANALYSIS DETAILS

For this analysis, we use  $N$  to represent the measured event-by-event observable, which is the event-by-event

net- $\Lambda$  multiplicity ( $\Delta N_\Lambda = N_\Lambda - N_{\bar{\Lambda}}$ ). The average value of the observable  $N$  is represented by  $\langle N \rangle$ . The deviation of  $N$  from the mean is given by  $\delta N = N - \langle N \rangle$ . The first three cumulants ( $C_1$ ,  $C_2$ , and  $C_3$ ), of the event-by-event distribution of  $N$  can be written as

$$C_1 = \langle N \rangle, \quad (1)$$

$$C_2 = \langle (\delta N)^2 \rangle, \quad (2)$$

$$C_3 = \langle (\delta N)^3 \rangle. \quad (3)$$

The mean, variance, and skewness of the distribution are related to the cumulants through

$$M = C_1, \quad \sigma^2 = C_2, \quad S = \frac{C_3}{(C_2)^{3/2}}. \quad (4)$$

The products and ratios presented in this analysis are

$$\frac{\sigma^2}{M} = \frac{C_2}{C_1}, \quad S\sigma = \frac{C_3}{C_2}. \quad (5)$$

The event-by-event  $\Lambda$  and  $\bar{\Lambda}$  multiplicities were measured for Au + Au minimum bias events at  $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4,$  and  $200$  GeV collision energies. The 39 and 62.4 GeV data were collected in 2010; all other energies were recorded in 2011. The number of events analyzed were  $16 \times 10^6, 33 \times 10^6, 77 \times 10^6, 27 \times 10^6,$  and  $199 \times 10^6$  for  $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4,$  and  $200$  GeV, respectively. Although the previously analyzed identified net-particle distributions in STAR for protons and kaons reached down to  $\sqrt{s_{NN}} = 7.7$  GeV, the available statistics for net- $\Lambda$ s, and in particular for the higher moments, were too small to extend the analysis below  $\sqrt{s_{NN}} = 19.6$  GeV. We hope to extend the analysis to the lower energies, even for the net- $\Lambda$  higher moments, with the datasets taken during the second beam energy scan campaign at RHIC. For the precise determination of the primary vertex (PV), the STAR time projection chamber (TPC) and the vertex position detectors (VPDs) were used. Only the collisions occurring within a distance of 30 cm from the center of the detector along the beam line were chosen. Effects from possible interactions of the beam with the beam pipe were minimized by rejecting collisions with a radial distance of 2 cm or greater from the center of the detector in the transverse plane. Pile-up events were removed by only selecting collisions with less than 2 cm difference between the PV measurements along the beam line obtained from the TPC and VPD.

The reconstruction of  $\Lambda$  ( $\bar{\Lambda}$ ) baryons was restricted to the decay channel:  $\Lambda$  ( $\bar{\Lambda}$ )  $\rightarrow p$  ( $\bar{p}$ ) +  $\pi^-$  ( $\pi^+$ ), which has a branching ratio of  $63.9\% \pm 0.5\%$ . The STAR TPC was used as the main tracking and charged-daughter-particle identification device in this analysis [28]. Ionization energy loss per unit length ( $dE/dx$ ) of a charged particle  $X$  in the TPC gas was used to calculate the quantity  $n\sigma_X$ , which is defined as

$$n\sigma_X = \frac{\ln[(dE/dx)_{\text{measured}}/(dE/dx)_{\text{theory}}]}{\sigma_X}, \quad (6)$$

where  $(dE/dx)_{\text{measured}}$  is the measured ionization energy loss from the TPC,  $(dE/dx)_{\text{theory}}$  is the theoretical expectation of the ionization energy loss from the Bichsel formula [29], and  $\sigma_X$  is the  $dE/dx$  resolution of the TPC. The identification

TABLE I. Topological cuts used for the extraction of  $V^0$ s event-by-event (DCA: distance of closest approach; PV: primary vertex).

Topological parameter	Cut
DCA of $p$ ( $\bar{p}$ ) to PV	$> 0.5$ cm
DCA of $\pi^-$ ( $\pi^+$ ) to PV	$> 1.5$ cm
DCA of $p$ ( $\bar{p}$ ) to $\pi^-$ ( $\pi^+$ )	$< 0.6$ cm
DCA of $V^0$ to PV	$< 0.5$ cm
$V^0$ decay length	$> 3.0$ cm

of species  $X$  [ $p$  ( $\bar{p}$ ) or  $\pi^+$  ( $\pi^-$ )] was done by imposing a cut,  $|n\sigma_X| < 2.0$ , within a rapidity coverage of  $|y| < 1.0$  and a transverse momentum of  $p_T > 0.05$  GeV/ $c$ . The invariant mass  $M_{\text{inv}}$  of  $\Lambda$  ( $\bar{\Lambda}$ ) was reconstructed by using the energy, momentum, and rest mass of the daughter particles  $p$  ( $\bar{p}$ ) and  $\pi^+$  ( $\pi^-$ ).

The selection of possible  $\Lambda$  and  $\bar{\Lambda}$  ( $V^0$ ) candidates was done by imposing an invariant-mass cut,  $1.11 < M_{\text{inv}}$  (GeV/ $c^2$ )  $< 1.12$  and applying topological cuts as shown in Table I. These tight cuts were applied in order to achieve a signal purity of greater than 90% for all collision energies. Figure 1 shows typical  $\Lambda$  and  $\bar{\Lambda}$  invariant-mass plots. No further background subtraction was applied, since studies, based on an analysis of the cumulants in the invariant-mass sidebands, showed that the remaining contamination contributes in a negligible way to the systematic error and to the absolute values of the cumulants themselves. A detailed description of particle reconstruction, track quality, decay vertex topology cuts, and calculation of the detection efficiency can be found in Refs. [30,31].

Only  $\Lambda$ s and  $\bar{\Lambda}$ s produced in a rapidity window  $|y| < 0.5$ , and with a transverse momentum within  $0.9 < p_T$  (GeV/ $c$ )  $< 2.0$  were used in this analysis. The low cutoff is driven by the falling reconstruction efficiency; the high cutoff is determined by the choice of using only the TPC for particle identification. The feed-down from multistrange baryon decays varies between 10% and 25% depending on the  $\Lambda$  transverse momentum and the collision energy [32,33]. This

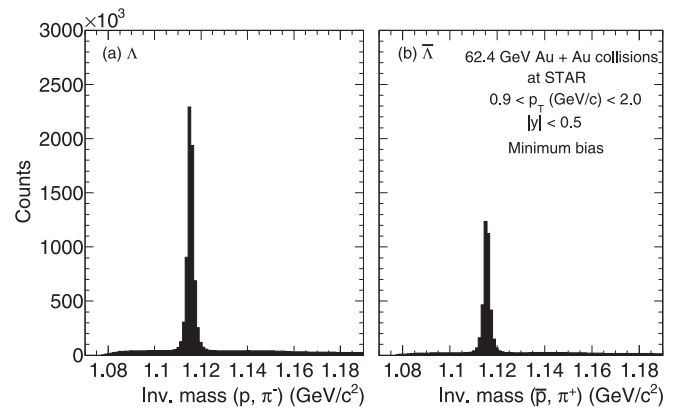


FIG. 1. Reconstructed invariant-mass distribution of (a)  $\Lambda$  and (b)  $\bar{\Lambda}$  for 62.4 GeV Au + Au collisions. Topological cuts shown in Table I are applied.

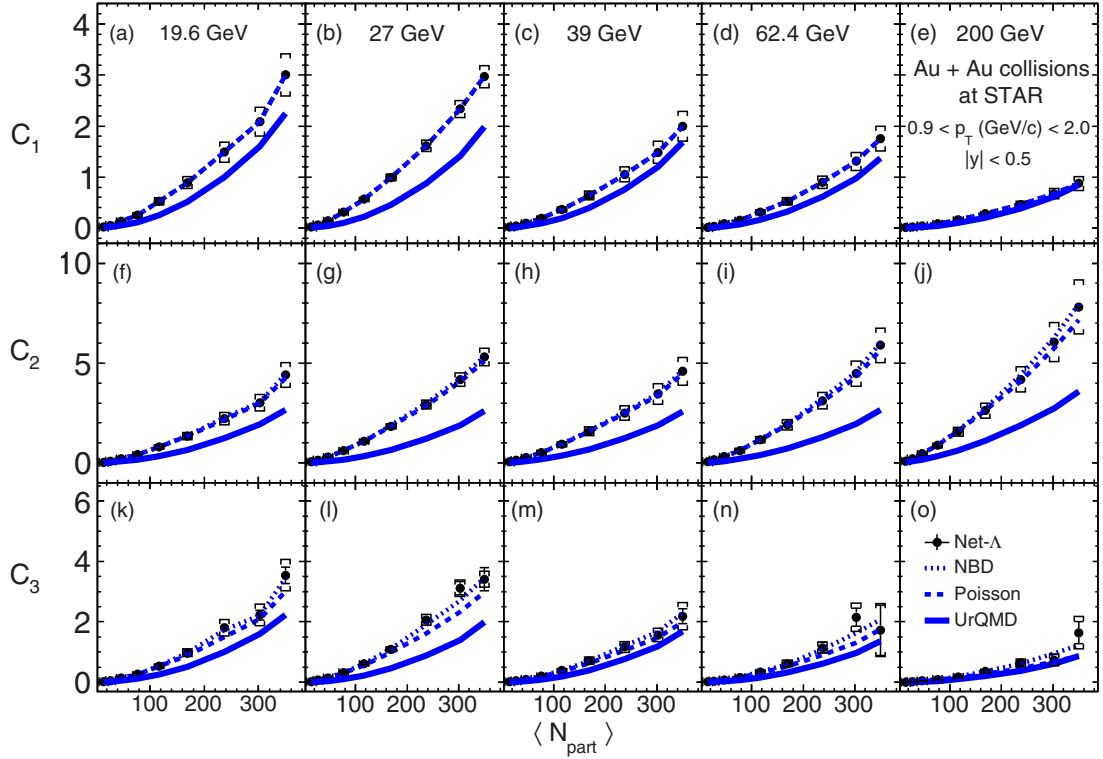


FIG. 2. Centrality dependence of first three single cumulants  $C_1$ ,  $C_2$ , and  $C_3$  of net- $\Lambda$  multiplicity distributions at Au + Au collision energies  $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4,$  and  $200$  GeV. NBD and Poisson baselines are presented by dashed lines. UrQMD predictions are shown in solid lines. Black vertical lines represent the statistical uncertainties and caps represent systematic uncertainties. Results are corrected for the reconstruction efficiency and the CBWC is applied.

effect reduces the single cumulants in Fig. 2 accordingly. It turns out, however, that the impact on the cumulant ratios shown in Figs. 3–9 is negligible, i.e., less than 1.5%, which can be treated as an additional systematic uncertainty. Thus no feed-down correction was applied to any of the cumulants.

The calculation of reconstruction efficiency was based on the probability of finding Monte Carlo generated particles after passing them through a TPC detector response simulation and then embedding them into real events prior to reconstruction. As an example, Table II shows the resulting  $p_T$ -averaged efficiencies for  $\Lambda$ s for the bins of highest collision centrality as a function of the beam energy. Within a chosen rapidity window, the particle reconstruction efficiency

TABLE II. Reconstruction efficiency of  $\Lambda$ , calculated in the transverse momentum range  $0.9 < p_T$  (GeV/c)  $< 2.0$ , and in centrality classes, 0%–5% to 20%–30%, using Eq. (7) for five beam energies: 19.6, 27, 39, 62.4, and 200 GeV.

Energy	Centrality			
	20%–30%	10%–20%	5%–10%	0%–5%
19.6 GeV	0.236	0.223	0.215	0.183
27 GeV	0.236	0.226	0.207	0.186
39 GeV	0.242	0.228	0.213	0.182
62.4 GeV	0.224	0.204	0.183	0.151
200 GeV	0.202	0.176	0.147	0.127

depends on the transverse momentum. The net- $\Lambda$  cumulants were corrected for the reconstruction efficiency following the method in Ref. [34], which takes the  $p_T$  dependence of the reconstruction efficiency into account. The number of  $p_T$  bins was varied from three to six bins in the aforementioned range without any discernible effect on the correction factors. The average reconstruction efficiency ( $\epsilon$ ) in each  $p_T$  bin was calculated as

$$\langle \epsilon \rangle = \frac{\int_a^b \left( \frac{dN}{dp_T} \right)_{RC} dp_T}{\int_a^b \left( \frac{dN}{dp_T} \right)_{MC} dp_T}, \quad (7)$$

where  $a$  and  $b$  stand for the lower and upper bounds of the corresponding  $p_T$  bin, respectively, and  $MC$  and  $RC$  represent the tracks generated by using Monte Carlo and the tracks reconstructed, respectively. The statistical uncertainty in the  $V^0$  reconstruction efficiency was estimated, by following the procedure in Ref. [35], to be 2.25% of the numbers quoted in Table II. Within the uncertainties,  $\Lambda$  and  $\bar{\Lambda}$  reconstruction efficiencies show negligible differences and are treated equally in the efficiency correction.

The collision centrality determination was done by using the efficiency uncorrected number of identified charged particles (also known as reference multiplicity) in the pseudorapidity interval  $|\eta| < 1.0$  by excluding protons and antiprotons in order to minimize possible self-correlations [36]. The classification of events into different collision centrality classes was achieved by using this reference multiplicity along with

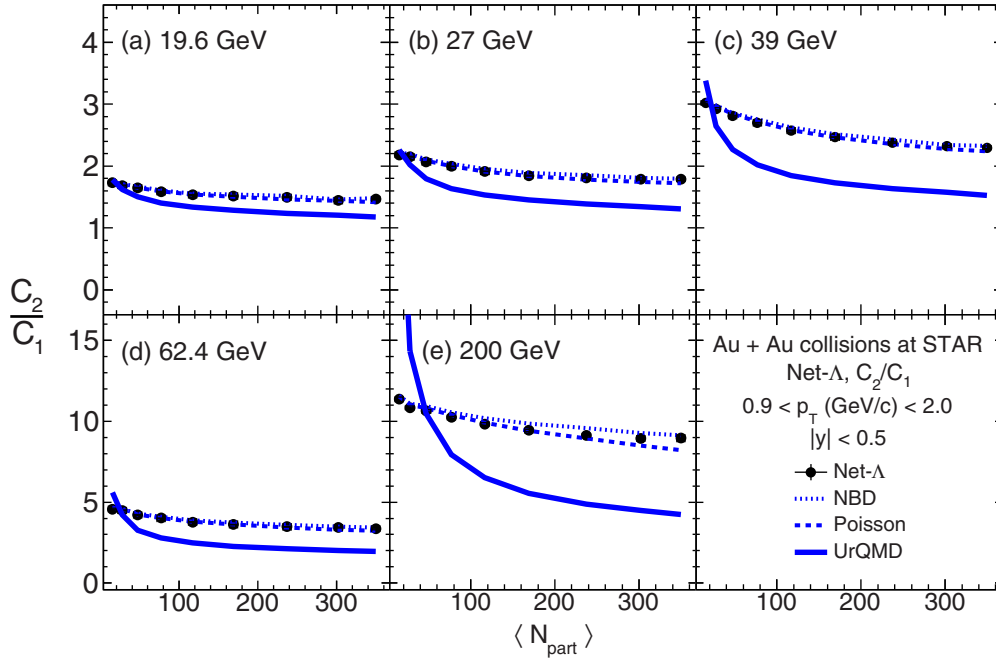


FIG. 3. Centrality dependence of net- $\Lambda$  cumulant ratio,  $C_2/C_1$  at Au + Au collision energies  $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4,$  and  $200$  GeV. NBD and Poisson baselines are presented by dashed lines. UrQMD predictions are shown in solid lines. Black vertical lines represent the statistical uncertainties and caps represent systematic uncertainties. Results are corrected for the reconstruction efficiency, and the CBWC is applied.

the Glauber model [37] simulations, in accordance with the procedure used in the published STAR net-proton analysis [21]. With this definition, the analysis was performed in nine

collision centrality classes: 0%–5%, 5%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, 50%–60%, 60%–70%, and 70%–80%.

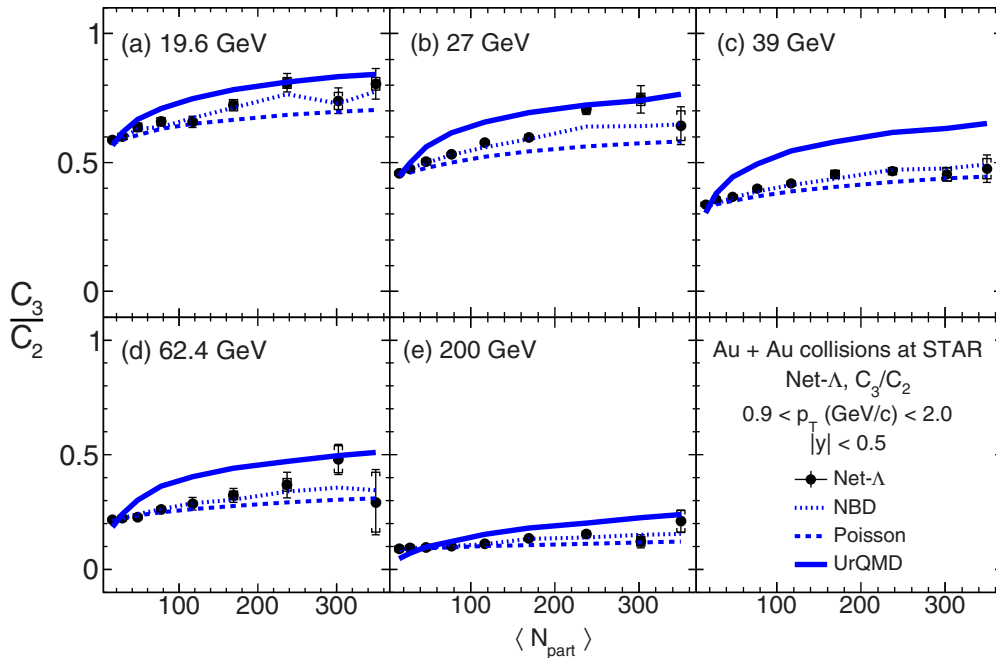


FIG. 4. Centrality dependence of net- $\Lambda$  cumulant ratio,  $C_3/C_2$  at Au + Au collision energies  $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4,$  and  $200$  GeV. NBD and Poisson baselines are presented by dashed lines. UrQMD predictions are shown in solid lines. Black vertical lines represent the statistical uncertainties and caps represent systematic uncertainties. Results are corrected for the reconstruction efficiency, and the CBWC is applied.

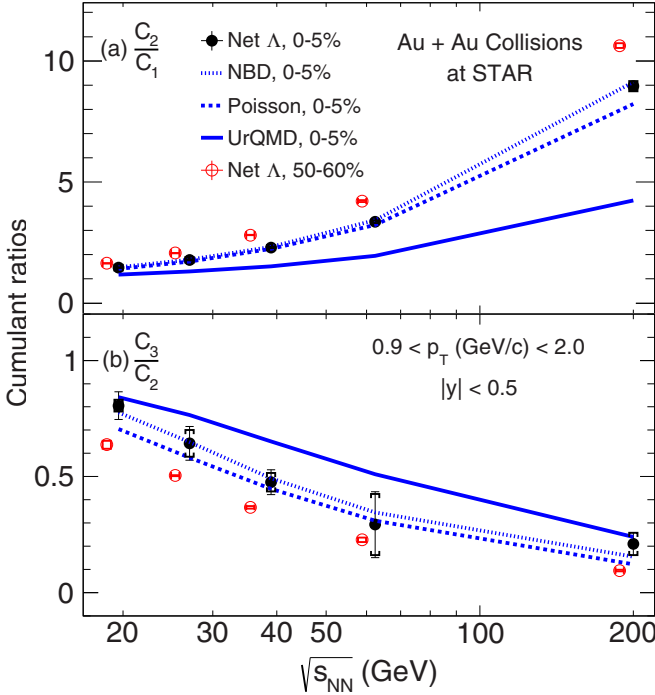


FIG. 5. Beam-energy dependence of net- $\Lambda$  cumulant ratios  $C_2/C_1$  and  $C_3/C_2$  in most-central (0%–5%) and peripheral (50%–60%) Au + Au collisions. NBD and Poisson baselines are presented by dashed lines. UrQMD predictions are shown in solid lines. Black vertical lines represent the statistical uncertainties and caps represent systematic uncertainties. Results are corrected for the reconstruction efficiency and the CBWC is applied. The red data points are shifted left for clarity.

The reconstruction efficiency depends on the collision centrality. Therefore, the efficiency correction was applied in each centrality class separately. As in previous STAR analyses, a binomial distribution of the efficiency loss was assumed [38]. Volume fluctuations due to the selection of finite centrality bins can lead to the so-called finite bin width effect. The results presented here were corrected for this effect by applying the centrality bin width correction (CBWC) [36].

For the net- $\Lambda$  cumulants up to the third order, the statistical uncertainties estimated by using the delta theorem method [36,39,40] and the subsampling method gave similar values when the number of subsamples was greater than 10. The statistical uncertainties presented in this paper were estimated by using the subsampling method with more than 10 subsamples in all collision energies.

The estimation of systematic uncertainties was done by varying the following topological and track cuts: (1) simultaneous variation of distance of closest approach (DCA) of  $p$  ( $\bar{p}$ ) to primary vertex (PV) and DCA of  $\pi^-$  ( $\pi^+$ ) to PV, (2) DCA of  $p$  ( $\bar{p}$ ) to  $\pi^-$  ( $\pi^+$ ), and (3) simultaneous variation of  $n\sigma_p$  ( $n\sigma_{\bar{p}}$ ) and  $n\sigma_{\pi^-}$  ( $n\sigma_{\pi^+}$ ). In addition, variations of the estimated uncertainty on the reconstruction efficiency ( $\pm 2.25\%$ ) were also included in the systematic uncertainty estimation. All sources were treated as uncorrelated. Table III shows a detailed breakdown of all relevant contributions at the highest beam energy. The variations as a function of the collision

TABLE III. Systematic uncertainty contributions from different sources (cuts and efficiency variations),  $n\sigma_p$  and  $n\sigma_{\pi^-}$  (NS), DCA of  $V^0$  to  $p$  and DCA of  $V^0$  to  $\pi^-$  (DCA-1), DCA of  $p$  to  $\pi^-$  (DCA-2) and efficiency variation (EV) for  $\sqrt{s_{NN}} = 200$  GeV collisions in 0%–5% centrality. The total uncertainty is based on the rms squared sum of all contribution. The single-source percentages are the relative weight to the total and thus are additive.

Cumulant	Source				Total
	NS	DCA-1	DCA-2	EV	
$C_1$	10.8%	2.3%	0.6%	1.6%	15.3%
$C_2$	11.7%	2.7%	1%	1.8%	17.2%
$C_3$	23.1%	4.4%	2.6%	2.8%	32.9%
$C_2/C_1$	1.3%	0.6%	0.4%	0.1%	2.4%
$C_3/C_2$	14.4%	5.5%	1.8%	1%	22.7%

energy are small, and the typical systematic uncertainties are on the order of 15% for  $C_1$ , 18% for  $C_2$ , and 30% for  $C_3$ . The biggest contribution comes from the uncertainty in the  $dE/dx$  measurements for particle identification ( $n\sigma$  variation). As can be seen in Table III, the apparent cancellation of source contributions in the systematics for the lowest cumulant ratio is not as dominant in the  $C_3/C_2$  ratio, since here the higher-order terms in the efficiency correction fluctuate more with varying the cuts used to determine the systematic uncertainties. The statistical uncertainties are presented by black vertical bars, and systematic uncertainties are presented by black caps in the figures of this paper.

### III. RESULTS

The centrality dependence of the net- $\Lambda$  single cumulants ( $C_1$ ,  $C_2$ , and  $C_3$ ) in Au + Au collisions is presented in Fig. 2 for five beam energies from  $\sqrt{s_{NN}} = 19.6$  to 200 GeV. The collision centrality is represented by the average number of participant nucleons ( $\langle N_{part} \rangle$ ) obtained from the Glauber model simulations. All three single cumulants show a steady increase as a function of increasing collision centrality at all collision energies due to the system volume dependence. For a fixed centrality, odd cumulants decrease as a function of increasing collision energy, which indicates that the  $\Lambda/\bar{\Lambda}$  ratio approaches unity at the highest RHIC energies. The Poisson baselines were calculated by considering the means of individual particle distributions ( $\Lambda$  and  $\bar{\Lambda}$ ), while the NBD expectations were calculated by using both means and variances. The Poisson and NBD expectations both show agreement with the measured single cumulants at all energies, within the statistical and systematic uncertainties. The description of the centrality of odd cumulants using UrQMD improves with increasing energy, but overall there is no satisfactory agreement with the transport code prediction for any of the cumulants over the range of the beam energy scan.

The volume-independent cumulant ratios,  $C_2/C_1$  ( $=\sigma^2/M$ ) and  $C_3/C_2$  ( $=S\sigma$ ), of net- $\Lambda$  distributions are presented in Figs. 3 and 4, respectively, as a function of collision centrality in Au + Au collisions for five beam energies from  $\sqrt{s_{NN}} = 19.6$  GeV to 200 GeV. The net- $\Lambda$   $C_2/C_1$  is nearly

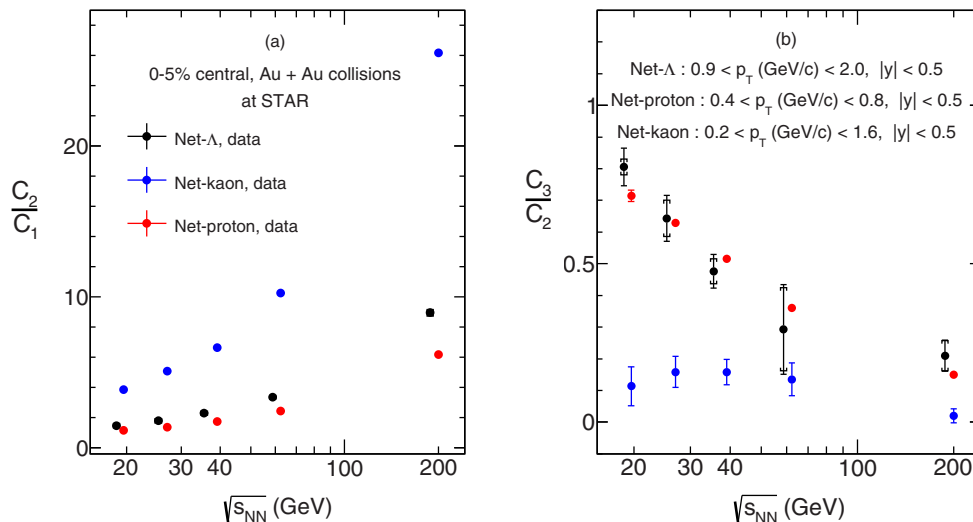


FIG. 6. Beam-energy dependence of net- $\Lambda$  (in black), net-proton (in red) and net-kaon (in blue) cumulant ratios, (a)  $C_2/C_1$  and (b)  $C_3/C_2$  in most-central (0%–5%) Au + Au collisions. The vertical lines represent the statistical uncertainties and caps represent systematic uncertainties. Results are corrected for the reconstruction efficiency and the CBWC is applied. The black data points are shifted left for clarity.

independent of the collision centrality due to the volume independence of the cumulant ratios, while it increases as a function of collision energy for a given centrality class, which is dominated by the energy dependence of  $C_1$ . Both the Poisson and NBD expectations show good agreement with the data. However, the UrQMD predictions show deviations from the data, which increase as a function of increasing collision energy. The major contribution to these deviations comes from the predictions for the net- $\Lambda$   $C_2$ . The net- $\Lambda$   $C_3/C_2$  measurement also shows only a weak dependence on the collision centrality. It decreases as a function of increasing collision energy mainly due to the energy dependence of the net- $\Lambda$   $C_3$ . The net- $\Lambda$   $C_3/C_2$  shows better agreement with the NBD expectations than with the Poisson baseline within the uncertainties, which could be an indication of less intra-event correlations between the produced  $\Lambda$ s and  $\bar{\Lambda}$ s [41].

The energy dependence of net- $\Lambda$   $C_2/C_1$  and  $C_3/C_2$  in the most-central (0%–5%) and the peripheral (50%–60%) Au + Au collisions for the five beam energies is presented in Fig. 5. The Poisson, NBD, and UrQMD expectations are shown for cumulant ratios measured in 0%–5% central collisions. Both the Poisson and NBD expectations show agreement with the measured net- $\Lambda$   $C_2/C_1$  and  $C_3/C_2$  within statistical and systematic uncertainties, except at 200 GeV where the data are better described by the NBD expectations than by the Poisson baseline. UrQMD significantly deviates from the measured net- $\Lambda$   $C_2/C_1$  at all energies above 19.6 GeV. The net- $\Lambda$   $C_3/C_2$  measured at  $\sqrt{s_{NN}} = 19.6$  and 200 GeV agrees with the UrQMD predictions for the most-central collisions, while it deviates from UrQMD expectations significantly at  $\sqrt{s_{NN}} = 27, 39$  and 62.4 GeV energies. There is no discernible presence of nonmonotonic behavior, which could indicate critical fluctuations, in the measured net- $\Lambda$  cumulant ratios as a function of collision energy.

Figure 6 compares the ratio measurements obtained for net- $\Lambda$  to those for net-kaons [20] and net-protons [21]. The

net- $\Lambda$  data follow more closely the net-proton data, which can be understood since the abundance and imbalance between particle and antiparticle for the  $\Lambda$  baryon is more closely aligned with the proton numbers than with the mesonic strange state [33,42].

To determine chemical freeze-out parameters, the energy dependence of the lowest net- $\Lambda$  cumulant ratio ( $C_2/C_1$ ) in most-central Au + Au collisions is compared with the cumulant ratios calculated, assuming different freeze-out (FO) conditions using the latest HRG model [22]. As shown in Ref. [43], ratios that contain higher-order moments are more sensitive to dynamical effects and thus lead to more unreliable results when FO parameters are extracted. We therefore focused on the high-resolution  $C_2/C_1$  measurement for our conclusions. Previous HRG model parameters that were based on the STAR net-proton and net-charge measurements [14] and net-kaon measurements [22], were used as benchmarks to compare with the net- $\Lambda$  measurements. In these earlier calculations a difference in freeze-out temperature of about 20 MeV was obtained between strange and light quark particles.

From the comparison of measured net- $\Lambda$   $C_2/C_1$  ratios with HRG predictions in Fig. 7(a), it is apparent that the measured net- $\Lambda$   $C_2/C_1$  ratio is closer to the  $C_2/C_1$  ratio calculated by assuming the kaon freeze-out conditions than the proton or charge freeze-out conditions. In other words the difference between the HRG calculations to the measured net- $\Lambda$   $C_2/C_1$  ratio becomes small when the freeze-out conditions extracted from the net-kaon fluctuations were used in the prediction. This observation is not trivial to interpret, but one possible explanation is that the strangeness conservation plays a more prominent role for the  $\Lambda$  baryon at freeze-out than the baryon number. For a complete understanding of this observation, further investigations, both theoretically and experimentally, are necessary. It is important to note that the measured net- $\Lambda$   $C_2/C_1$  ratio is much closer to the measured net-proton  $C_2/C_1$  ratio [see Fig. 6(b)], whereas the deduced



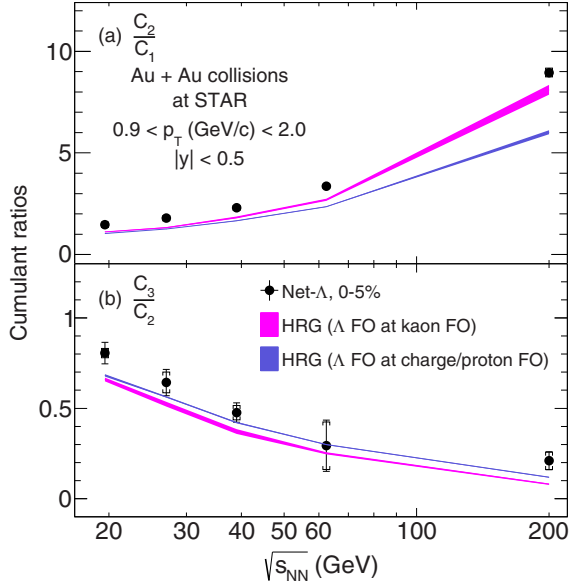


FIG. 7. Black markers show the beam-energy dependence of the measured net- $\Lambda$  cumulant ratios, (a)  $C_2/C_1$  and (b)  $C_3/C_2$  in most-central (0%–5%) Au + Au collisions. Magenta bands show the net- $\Lambda$  cumulant ratios from a HRG calculation [22] assuming  $\Lambda$ s freeze-out under the same FO conditions as the kaons. Blue bands show the net- $\Lambda$  cumulant ratios from the same HRG calculation assuming  $\Lambda$ s freeze-out under the same FO conditions as the charged particles and protons. Results are corrected for the reconstruction efficiency, and the CBWC is applied. The vertical bars and the caps represent the statistical and systematic uncertainties, respectively. Uncertainties in the HRG calculations are shown by the width of the bands.

freeze-out temperature from the net- $\Lambda$   $C_2/C_1$  ratio is closer to the deduced temperature from the net-kaon  $C_2/C_1$  ratio [see Fig. 7(a)]. This points at the fact that the measured net-cumulants are dominated by the particle to antiparticle ratios, but the deduced temperatures are driven by the resonance contributions to the final ratios.

In contrast to any critical endpoint searches, the chemical freeze-out is presently best determined in the lower cumulant ratios that have the smallest error bars. The temperature differences found in the HRG calculations are less pronounced in the  $C_3/C_2$  ratio shown in Fig. 7(b) and the error bars of the measurement are larger, which prohibits a definitive statement on the basis of the higher cumulant ratio.

Finally, the rapidity dependence of net- $\Lambda$  cumulant ratios has been investigated for the most-central 200 GeV Au + Au collisions. Figure 8 shows a comparison of the cumulant ratios to NBD expectations as a function of  $\Delta y$ , i.e., the rapidity window around midrapidity. Both cumulant ratios show a weak dependence on the selected rapidity window and generally good agreement with the NBD baseline. Figure 9 presents the ratio of the net- $\Lambda$   $C_2$  to a NBD baseline as a function of relative rapidity coverage  $\Delta y$  normalized by  $\Delta y_{\text{beam}}$ , for  $\sqrt{s_{NN}} = 19.6$  and 200 GeV Au + Au collisions at 0%–5% centrality.

The potential impact of baryon number conservation as a function of the detector acceptance has been addressed

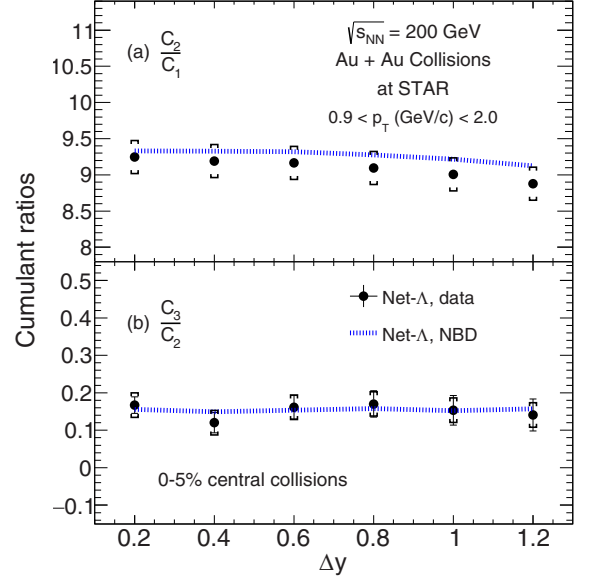


FIG. 8. Rapidity dependence of net- $\Lambda$  cumulant ratios (a)  $C_2/C_1$  and (b)  $C_3/C_2$  in  $\sqrt{s_{NN}} = 200$  GeV Au + Au collisions at 0%–5% centrality. Dashed lines show the NBD expectations. Vertical error bars represent the statistical uncertainties and caps represent the systematic uncertainties. Results are corrected for the reconstruction efficiency and the CBWC is applied.

recently in the literature [44,45]. When comparing our results to a calculation based on this approach, but taking into account the fact that the  $\Lambda$  carries both baryon number and strangeness, we find the solid lines shown in Fig. 9. Here the acceptance factors ( $\alpha_B$  and  $\alpha_s$ ) are defined as the ratio between the average number of  $\Lambda$ s in the selected acceptance ( $\langle N_{\Lambda}^{\text{acc}} \rangle$ ) over the average number of total baryons ( $\langle N_B^{4\pi} \rangle$ ) or total strangeness ( $\langle N_s^{4\pi} \rangle$ ) in the full phase space, respectively.  $\langle N_s^{4\pi} \rangle$  is defined as the number of strange quarks confined in strange hadrons in  $4\pi$ . The quantities  $\langle N_B^{4\pi} \rangle$  and  $\langle N_s^{4\pi} \rangle$  were calculated by using the UrQMD model. The  $4\pi$  particle

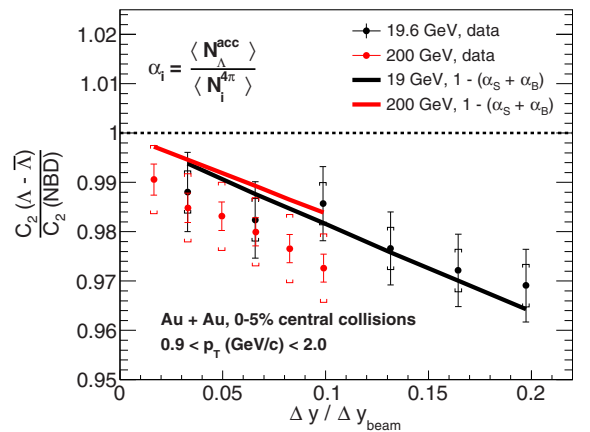


FIG. 9. Rapidity dependence of the normalized  $C_2(\Lambda-\bar{\Lambda})$  in most-central (0%–5%) collisions for 19.6 and 200 GeV collision energies. The solid lines show the expected effects from baryon number  $B$  and strangeness  $s$  conservation.

yields are adequately described by this model in the BES energy range. The acceptance factors,  $\alpha_B$  and  $\alpha_s$ , were calculated separately and added to approximate the anticipated correction due to the combined quantum number conservation effect. The relative contribution of each acceptance factor is slightly energy dependent. At the lower energy  $\alpha_s$  dominates, whereas at the highest RHIC energies the  $\alpha_B$  contribution is stronger. As shown in Fig. 9, the combined factor accounts well for the rapidity dependence at  $\sqrt{s_{NN}} = 19.6$  GeV. The beam-energy dependence is not perfectly captured, but one should note that the overall effect on the final result is small at all energies ( $<3\%$ ), which reflects the number of protons and  $\Lambda$ s in the detector acceptance. A more detailed study of the conservation effects in the beam energy scan regime, i.e., in the region where the varying baryon stopping plays an important role, might also require a more local baryon number conservation approach, as was suggested recently [46].

#### IV. SUMMARY

The fluctuations of conserved quantum numbers such as net-charge, net-baryon number, and net-strangeness provide useful information about the nuclear matter phase transition. Fluctuations of measured net-particle multiplicity distributions in the medium produced after the heavy-ion collisions have been successfully used as proxies for conserved quantum number fluctuations. The measured cumulant ratios of net-charge, net-proton, and net-kaon multiplicity distributions at STAR have been compared with HRG calculations to extract the freeze-out parameters in the QCD crossover region. The  $\Lambda$  baryon carries both baryon and strangeness quantum numbers. This paper presents the first measurements of the centrality, collision energy, and rapidity dependence of net- $\Lambda$  single cumulants ( $C_1, C_2, C_3$ ) and cumulant ratios ( $C_2/C_1, C_3/C_2$ ) in Au + Au collisions measured at the STAR detector for five beam energies ( $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4, \text{ and } 200$  GeV). Results were compared with Poisson, NBD, UrQMD, and HRG model expectations. The comparison of these net- $\Lambda$  fluctuation measurements with the latest HRG model provides important information needed for understanding the dominant quantum number specific contributions to the hadronization process.

Both Poisson and NBD expectations were able to describe the centrality and collision-energy dependence of the net- $\Lambda$  single cumulants ( $C_1, C_2$ , and  $C_3$ ) and cumulant ratios ( $C_2/C_1$  and  $C_3/C_2$ ) fairly well. This indicates that any onset of critical or nonmonotonic behavior is not apparent for the energies and cumulants studied here, which is consistent with the results of previous STAR/BES-I fluctuation analyses.

In  $\sqrt{s_{NN}} = 200$  GeV Au + Au collisions, the net- $\Lambda$  cumulant ratios show better agreement with the NBD expectations than with the Poisson baseline. The UrQMD predictions show good agreement with the odd cumulants within the uncertainties at 200 GeV, while there is a considerable deviation from the measured  $C_2$  at all energies. The rapidity dependence of the net- $\Lambda$  cumulant ratios, based on our results at 200 GeV, is small. Nevertheless, single cumulants deviate at the level of a few percent from the NBD baseline over the measured rapidity interval at all beam energies, which cannot be attributed to baryon number conservation alone. Only when baryon number and strangeness conservation are combined is the difference well explained.

The lowest net- $\Lambda$  cumulant ratio,  $C_2/C_1$ , was compared with recent HRG model calculations in order to obtain the proper chemical freeze-out scenario for the strange baryon. The deviation of the HRG calculations from the measured  $C_2/C_1$  ratio becomes small when the HRG model calculations were performed by using the freeze-out conditions extracted considering strange (kaon) net-particle fluctuations, but not when the nonstrange (charge and proton) net-particle fluctuations were considered. Further experimental and theoretical progress is needed in order to understand whether this observation is due to a flavor hierarchy in the freeze-out parameters, which could lead to possible sequential hadronization.

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