CHARGE DEPENDENCE AND SCALING PROPERTIES OF DYNAMICAL K/π, p/π, AND K/p FLUCTUATIONS FROM THE STAR EXPERIMENT*

Terence J. Tarnowsky

for the STAR Collaboration

National Superconducting Cyclotron Laboratory, Michigan State University
East Lansing, MI, USA

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Dynamical fluctuations in global conserved quantities such as baryon number, strangeness, or charge may be enhanced near a QCD critical point. Charge dependent results from new measurements of dynamical K/π, p/π, and K/p ratio fluctuations are presented. The STAR experiment has performed a comprehensive study of the energy dependence of these dynamical fluctuations in Au+Au collisions at the energies $\sqrt{s_{NN}} = 7.7$–$200\,\mathrm{GeV}$ using the observable, ν_{dyn}. These results are compared to previous measurements and to theoretical predictions. Various proposed scaling scenarios that attempt to remove the intrinsic volume dependence of ν_{dyn} and to simplify comparisons between experimental measurements are also considered. Constructing an intensive quantity allows for a direct connection to thermodynamic predictions.

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1. Introduction

Fluctuations and correlations are well known signatures of phase transitions. In particular, the quark/gluon to hadronic phase transition may lead to significant fluctuations [1]. In 2010, the Relativistic Heavy Ion Collider (RHIC) began a program to search for the QCD critical point. This involves an "energy scan" of Au+Au collisions from top collision energy ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$) down to energies as low as $\sqrt{s_{NN}} = 7.7\,\mathrm{GeV}$ [2]. This

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critical point search will make use of the study of correlations and fluctuations, particularly those that could be enhanced during a phase transition that passes close to a critical point.

$\nu_{\rm dyn}$ quantifies deviations in the particle ratios from those expected for an ideal statistical Poissonian distribution [3, 4]. The definition of $\nu_{{\rm dyn},K/\pi}$ (describing fluctuations in the K/π ratio) is,

$$\nu_{{\rm dyn},K/\pi} = \frac{\langle N_K(N_K-1)\rangle}{\langle N_K\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_K N_\pi\rangle}{\langle N_K\rangle\langle N_\pi\rangle}\,. \tag{1}$$

A formula similar to (1) can be constructed for p/π and K/p ratio fluctuations. Additional information about $\nu_{\rm dyn}$ can be found in [4, 5, 6]. An in-depth study of K/π fluctuations in Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV was previously carried out by the STAR experiment [5].

2. Results and discussion

Current results on the energy dependence of measured dynamical particle ratio fluctuations from the STAR experiment are shown in figures 1, 2 (a), and 2 (b). These include previously presented results from the inclusive charged K/π, p/π, and K/p ratios [9], as well as initial results on the charge dependence of these dynamical ratio fluctuations as a function of collision energy in the search for the QCD critical point at RHIC. Results from previous measurements of K/π fluctuations at $\sqrt{s_{NN}} = 62.4$ and 200 GeV for both charge dependent and independent cases are discussed in [5].

Figure 1 shows $\nu_{{\rm dyn},K/\pi}$ as a function of energy from the STAR experiment, measured in central 0–5% Au+Au collisions at the energies $\sqrt{s_{NN}} = 7.7$, 11.5, 19.6, 39, and 200 GeV. The total dynamical K/π fluctuations (filled stars) are constructed as $K/\pi = (K^+ + K^-)/(\pi^+ + \pi^-)$. Dynamical fluctuations can also be constructed for different charge combinations. The combinations include: $++$, $--$, $+-$, and $-+$. The average of the same sign (open stars) and opposite sign (open crosses) K/π fluctuations are also shown in figure 1. The charge dependent fluctuations provide a more detailed picture of how particle production mechanisms affect the dynamical fluctuations. Also shown are published measurements of $\sigma_{{\rm dyn},K/\pi}$ from central 0–3.5% Pb+Pb collisions from the NA49 experiment [10], converted to $\nu_{{\rm dyn},K/\pi}$ using $\sigma^2_{\rm dyn} \approx \nu_{\rm dyn}$. This was also done for p/π and K/p $\sigma_{\rm dyn}$ results from NA49. STAR has also directly calculated $\sigma_{{\rm dyn},K/\pi}$ and experimentally verified the relationship between $\nu_{\rm dyn}$ and $\sigma_{\rm dyn}$. The total charged dynamical K/π fluctuations measured by both STAR and NA49 are positive. STAR observes no large change in dynamical K/π fluctuations between the energies from $\sqrt{s_{NN}} = 7.7$–200 GeV.

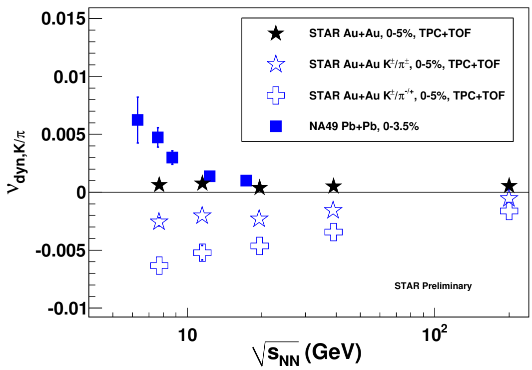

Fig. 1. Results for the measurement of inclusive charged (filled stars) and average same-sign (open stars) and opposite-sign (open crosses), charge dependent $\nu_{\mathrm{dyn},K/\pi}$.

The charge dependent dynamical K/π fluctuations measured by STAR are negative at all energies for both the same and opposite sign charge combinations. Both charged sign combinations are close in magnitude at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, but the average opposite sign dynamical fluctuations become more negative with decreasing energy, faster, than the same sign fluctuations. Fluctuations in opposite-sign charge combinations tend to be more negative overall than their same-sign counterparts due to stronger cross-correlation (immediate local charge conservation) of two opposite sign particles produced by a single resonance decay. Additionally, the charge independent fluctuations are not a simple sum of the charge dependent components. This indicates that while the charge dependent results are always negative, the charge independent results can be positive.

Figure 2 (a) shows $\nu_{\mathrm{dyn},p/\pi}$ as a function of energy from the STAR experiment, measured in central 0–5% Au+Au collisions at the energies $\sqrt{s_{NN}} = 7.7$, 11.5, 19.6, 39, and 200 GeV. The total dynamical p/π fluctuations (filled stars) are constructed as $p/\pi = (p^+ + p^-)/(\pi^+ + \pi^-)$. As discussed for K/π fluctuations, dynamical fluctuations for p/π can also be constructed for different charge combinations. The average of the same sign (open stars) and opposite sign (open crosses) p/π fluctuations are also included in figure 2 (a). Also included are published measurements from the NA49 experiment [10].

The total charged dynamical p/π fluctuations measured by both STAR and NA49 are negative and become more negative with decreasing collision energy. The two experiments measure coincident values for dynamical p/π fluctuations at energies below $\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$.

Unlike K/π fluctuations, both charge independent and charge dependent dynamical p/π fluctuations are always negative. This indicates a strong cross-correlation exists between produced protons and pions at all ener-

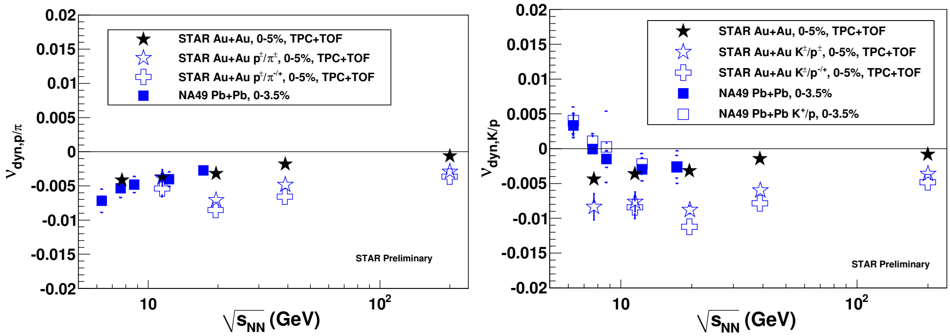

Fig. 2. Results for the measurement of inclusive charged (filled stars) and average same-sign (open stars) and opposite-sign (open crosses), charge dependent $\nu_{\mathrm{dyn},p/\pi}$ (left) and $\nu_{\mathrm{dyn},K/p}$ (right).

gies. The strong decay of a Δ baryon is a large contributor to this cross-correlation. Examples of this decay that produce cross-correlations would be $\Delta^{++} \rightarrow p^{+} + \pi^{+}$ or $\Delta^{0} \rightarrow p^{+} + \pi^{-}$.

The charge dependent results for dynamical p/π fluctuations become more negative at about the same rate with decreasing collision energy, until below $\sqrt{s_{NN}} = 19.6$ GeV. The anti-proton yield drops dramatically below this energy. The measured $\overline{p}/p$ ratio decreases by $\approx$ an order of magnitude between $\sqrt{s_{NN}} = 17.3$ and 7.6, from 0.1 to 0.01 [11]. Additional study is required of fluctuations involving anti-protons at the lowest energies of $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV.

The measurement of $\nu_{\mathrm{dyn},K/p}$ as a function of energy from the STAR experiment, measured in central 0–5% Au+Au collisions at the energies $\sqrt{s_{NN}} = 7.7$, 11.5, 19.6, 39, and 200 GeV is shown in figure 2 (b). The total dynamical K/p fluctuations (filled stars) are constructed as $K/p = (K^{+} + K^{-})/(p^{+} + p^{-})$. Different charge combinations of dynamical K/p fluctuations are also examined. The average of the same sign (open stars) and opposite sign (open crosses) K/p fluctuations are presented in figure 2 (b). Also included are published measurements from the NA49 experiment [12]. Similar to p/π fluctuations, both charge independent and charge dependent dynamical K/p fluctuations are always negative. This indicates a strong cross-correlation exists between produced kaons and protons at all energies. The charge independent dynamical K/p fluctuations become more negative as the collision energy is decreased. Charge dependent dynamical K/p fluctuations become more negative from $\sqrt{s_{NN}} = 200$ to 19.6 GeV, below which the fluctuations are almost constant. Results from the NA49 experiment for both charge independent and charge dependent K/p fluctuations demonstrate a rapid increase below energies of $\sqrt{s_{NN}} = 8$ GeV and actually cross zero and become positive at the lowest energies measured. The results from STAR are consistent with negative dynamical K/p fluctuations at all energies. However, as for dynamical p/π fluctuations, the K/p fluctuations involving anti-protons at the two lowest energies measured by STAR are still under study.

As defined, $\nu_{\rm dyn}$ is an extensive variable, by virtue of an explicit system-size (multiplicity) dependence. Therefore, as the system-size increases, $\nu_{\rm dyn}$ should decrease (toward zero). This is seen in the centrality dependence of $\nu_{\rm dyn}$, where it approaches zero from peripheral to central collisions where the multiplicity increases [5]. This also accounts for a part of the overall trends in the energy dependence of $\nu_{\rm dyn}$. To create an intensive variable, $\nu_{\rm dyn}$ scaled by the system-size (particle multiplicity) can be studied. In [5], the scaling used are values of $dN/d\eta$ for each centrality, corrected for detector efficiency and acceptance. For this study, the uncorrected values of $dN/d\eta$ from 0–5% central Au+Au collisions at each energy are used.

Figures 3 (a), and 3 (b) show the values of $\nu_{{\rm dyn},K/\pi}$, $\nu_{{\rm dyn},p/\pi}$, and $\nu_{{\rm dyn},K/p}$, respectively, scaled by uncorrected charged particle multiplicity $dN/d\eta$. Figures 3 (a) and 3 (b) also include the scaling result if average uncorrected number of protons + anti-protons ($\langle p\rangle$) is used. Figures 3 (a) and 3 (b) indicates that the uncorrected $dN/d\eta$ scaled fluctuations involving protons reach a minimum value between $\sqrt{s_{NN}} = 7.7$ and 19.6 GeV, before increasing toward zero at higher energies. Since the net-baryon density (μ_B) also changes with energy, further investigation of this behavior is required. The smooth scaling with only $\langle p\rangle$ could reflect the change in net-baryon number with energy, as the ratio of μ_B at $\sqrt{s_{NN}} = 7.7$ and 200 is similar to the ratio of $\langle p\rangle * \nu_{{\rm dyn},p/\pi}$ at those energies.

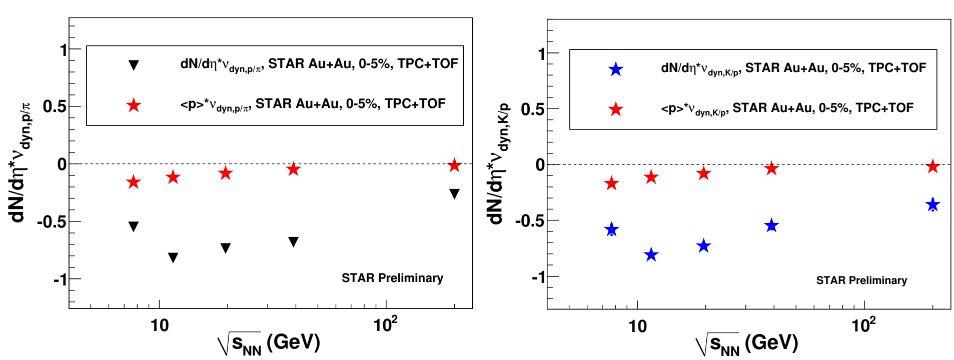

Fig. 3. Results for the measurement of $\nu_{{\rm dyn},p/\pi}$ (left) and $\nu_{{\rm dyn},K/p}$ (right) scaled by uncorrected charged particle multiplicity, $dN/d\eta$, from central 0–5% Au+Au collisions at $\sqrt{s_{NN}} = 7.7$–200 GeV.

3. Summary

Results from dynamical particle ratio fluctuations (K/π, p/π, and K/p) and new results on the charge dependence of dynamical fluctuations have been presented from data acquired in Au+Au collisions at energies from $\sqrt{s_{NN}}$ = 7.7–200 GeV. Also discussed are initial results from multiplicity scaled dynamical fluctuations of all three particle ratios at energies from $\sqrt{s_{NN}}$ = 7.7–200 GeV.

The charge dependent dynamical fluctuations provide additional insight into particle production as a function of energy. Further study is necessary at all energies, including plotting each charge combination separately. Uncorrected multiplicity scaled dynamical p/π and K/p fluctuations become more negative between $\sqrt{s_{NN}} = 7.7$ and 19.6 GeV, before increasing toward zero at higher energies.

Additional data points at $\sqrt{s_{NN}} = 27$ and 62.4 GeV are under study and will complete the excitation function for the first phase of the RHIC energy scan to search for the QCD critical point.

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