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 $K/\pi$, $p/\pi$, 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 $\sqrt{s_{NN}} = 7.7–200\text{GeV}$ using the observable, $\nu_{\text{dyn}}$. These results are compared to previous measurements and to theoretical predictions. Various proposed scaling scenarios that attempt to remove the intrinsic volume dependence of $\nu_{\text{dyn}}$ 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 ($\sqrt{s_{NN}} = 200\text{GeV}$) down to energies as low as $\sqrt{s_{NN}} = 7.7\text{GeV}$ [2].
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.

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

\[
\nu_{\text{dyn},K/\pi} = \frac{\langle N_K (N_K - 1) \rangle}{\langle N_K \rangle^2} + \frac{\langle N_\pi (N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2\frac{\langle N_K N_\pi \rangle}{\langle N_K \rangle \langle N_\pi \rangle}.
\]

(1)

A formula similar to (1) can be constructed for \( p/\pi \) and \( K/p \) ratio fluctuations. Additional information about \( \nu_{\text{dyn}} \) can be found in [4, 5, 6]. An in-depth study of \( K/\pi \) 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 \( K/\pi \), \( p/\pi \), 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 \( K/\pi \) fluctuations at \( \sqrt{s_{NN}} = 62.4 \) and 200 GeV for both charge dependent and independent cases are discussed in [5].

Figure 1 shows \( \nu_{\text{dyn},K/\pi} \) 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 \( K/\pi \) 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) \( K/\pi \) 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 \( \sigma_{\text{dyn},K/\pi} \) from central 0–3.5% Pb+Pb collisions from the NA49 experiment [10], converted to \( \nu_{\text{dyn},K/\pi} \) using \( \sigma_{\text{dyn}}^2 \approx \nu_{\text{dyn}} \). This was also done for \( p/\pi \) and \( K/p \) \( \sigma_{\text{dyn}} \) results from NA49. STAR has also directly calculated \( \sigma_{\text{dyn},K/\pi} \) and experimentally verified the relationship between \( \nu_{\text{dyn}} \) and \( \sigma_{\text{dyn}} \). The total charged dynamical \( K/\pi \) fluctuations measured by both STAR and NA49 are positive. STAR observes no large change in dynamical \( K/\pi \) fluctuations between the energies from \( \sqrt{s_{NN}} = 7.7–200 \) GeV.
The charge dependent dynamical $K/\pi$ 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 $\sqrt{s_{NN}} = 200$ 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 $\nu_{\text{dyn},p/\pi}$ 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 $p/\pi$ fluctuations (filled stars) are constructed as $p/\pi = (p^+ + p^-)/ (\pi^+ + \pi^-)$. As discussed for $K/\pi$ fluctuations, dynamical fluctuations for $p/\pi$ can also be constructed for different charge combinations. The average of the same sign (open stars) and opposite sign (open crosses) $p/\pi$ fluctuations are also included in figure 2 (a). Also included are published measurements from the NA49 experiment [10].

The total charged dynamical $p/\pi$ 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 $p/\pi$ fluctuations at energies below $\sqrt{s_{NN}} = 19.6$ GeV.

Unlike $K/\pi$ fluctuations, both charge independent and charge dependent dynamical $p/\pi$ 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 $\nu_{\text{dyn},p/\pi}$ (left) and $\nu_{\text{dyn},K/p}$ (right).

gies. The strong decay of a $\Delta$ 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 $p/\pi$ 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 $\bar{p}/p$ 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 $\nu_{\text{dyn},K/p}$ 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 $p/\pi$ 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 $p/\pi$ fluctuations, the $K/p$ fluctuations involving anti-protons at the two lowest energies measured by STAR are still under study.

As defined, $\nu_{\text{dyn}}$ is an extensive variable, by virtue of an explicit system-size (multiplicity) dependence. Therefore, as the system-size increases, $\nu_{\text{dyn}}$ should decrease (toward zero). This is seen in the centrality dependence of $\nu_{\text{dyn}}$, 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 $\nu_{\text{dyn}}$. To create an intensive variable, $\nu_{\text{dyn}}$ 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 $\nu_{\text{dyn},K/\pi}$, $\nu_{\text{dyn},p/\pi}$, and $\nu_{\text{dyn},K/p}$, 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 ($\mu_B$) 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 $\mu_B$ at $\sqrt{s_{NN}} = 7.7$ and 200 is similar to the ratio of $\langle p \rangle \times \nu_{\text{dyn},p/\pi}$ at those energies.

Fig. 3. Results for the measurement of $\nu_{\text{dyn},p/\pi}$ (left) and $\nu_{\text{dyn},K/p}$ (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 ($K/\pi$, $p/\pi$, 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 $p/\pi$ 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.

REFERENCES