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SEARCHING FOR THE QCD CRITICAL POINT WITH CORRELATION AND FLUCTUATION MEASUREMENTS FROM PHENIX*

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The PHENIX experiment has conducted searches for the QCD critical point with measurements of multiplicity fluctuations, transverse momentum fluctuations, event-by-event kaon-to-pion ratios, and azimuthal correlations. Measurements have been made in several collision systems as a function of centrality and transverse momentum. The results do not show significant evidence of critical behavior in the collision systems and energies studied, although several interesting features are discussed.

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1. Introduction

Recent work with lattice gauge theory simulations indicate that the phase diagram of Quantum Chromodynamics (QCD) may contain a first-order transition line between the hadron gas phase and the strongly-coupled Quark–Gluon Plasma (sQGP) phase that terminates at a critical point [1]. This property is observed in many common liquids, including water. Near the QCD critical point, several thermodynamic properties of the system will diverge with a power law behavior in the variable $\varepsilon = (T - T_{\mathrm{C}})/T_{\mathrm{C}}$, where T_{C} is the critical temperature. Here, several measurements that may be sensitive to this critical behavior are discussed.

2. Multiplicity, $\langle p_{\mathrm{T}}\rangle$, and K/π fluctuations

In the Grand Canonical Ensemble, the variance and the mean of the particle number, N, can be directly related to the compressibility, k_{T}: $\omega_N = \mathrm{var}(N)/N = k_{\mathrm{B}}T(N/V)\,k_{\mathrm{T}}$, where k_{B} is Boltzmann constant, T is the

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temperature, and V is the volume [2]. Near the critical point, the compressibility diverges with a power law behavior with exponent γ: $k_{\mathrm{T}} \propto \varepsilon^{-\gamma}$. The measurement of event-by-event fluctuations in the multiplicity of charged hadrons may be sensitive to critical behavior in the system. PHENIX has surveyed the behavior of inclusive charged particle multiplicity fluctuations as a function of centrality and transverse momentum in $\sqrt{s_{\mathrm{NN}}} = 62.4\,\mathrm{GeV}$ and 200 GeV Au+Au collisions, and in $\sqrt{s_{\mathrm{NN}}} = 22.5$, 62.4, and 200 GeV Cu+Cu collisions.

Since multiplicity fluctuations are well described by Negative Binomial Distributions (NBD) in both elementary [3] and heavy ion collisions [4], the data for a given centrality and p_{T} bin are fit to an NBD from which the mean and variance are determined. Due to the finite width of each centrality bin, there is a non-dynamic component of the observed fluctuations that is present due to fluctuations in the impact parameter within a centrality bin. The magnitude of this component is estimated using the HIJING event generator [5], which well reproduces the mean multiplicity of RHIC collisions [6]. The estimate is performed by comparing fluctuations from simulated events with a fixed impact parameter to events with a range of impact parameters covering the width of each centrality bin, as determined from Glauber model simulations. The data are corrected to remove the impact parameter fluctuation component.

Baseline comparisons are made to the participant superposition model, in which the total multiplicity fluctuations can be expressed in terms of the scaled variance [7], $\omega_N = \omega_\nu + \mu_{\mathrm{WN}}\, \omega_{N_{\mathrm{part}}}$, where ω_ν are the fluctuations from each individual source, $\omega_{N_{\mathrm{part}}}$ are the fluctuations of the number of sources, and μ_{WN} is the mean multiplicity per wounded nucleon. The second term includes non-dynamic contributions from impact parameter fluctuations along with additional fluctuations in the number of participants for a fixed impact parameter. Ideally, the second term is nearly nullified after applying the previously described corrections, so the resulting fluctuations are independent of centrality as well as collision species. Baseline comparisons at 200 GeV are facilitated by PHENIX measurements of charged particle multiplicity fluctuations in minimum bias 200 GeV $p+p$ collisions with mean $\mu = 0.32 \pm 0.003$, scaled variance $\omega = 1.17 \pm 0.01$, and NBD fit parameter $k_{\mathrm{NBD}} = 1.88 \pm 0.01$.

The scaled variance as a function of the number of participating nucleons, N_{part}, over the p_{T} range $0.2 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}/c$ is shown in Fig. 1 for Au+Au collisions. For all centralities, the scaled variance values consistently lie above the Poisson distribution value of 1.0. In all collision systems, the minimum scaled variance occurs in the most central collisions and then begins to increase as the centrality decreases. A similar centrality-dependent trend of the scaled variance has also been observed at the SPS in low energy Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 17.3\,\mathrm{GeV}$, measured by experiment NA49 [8],

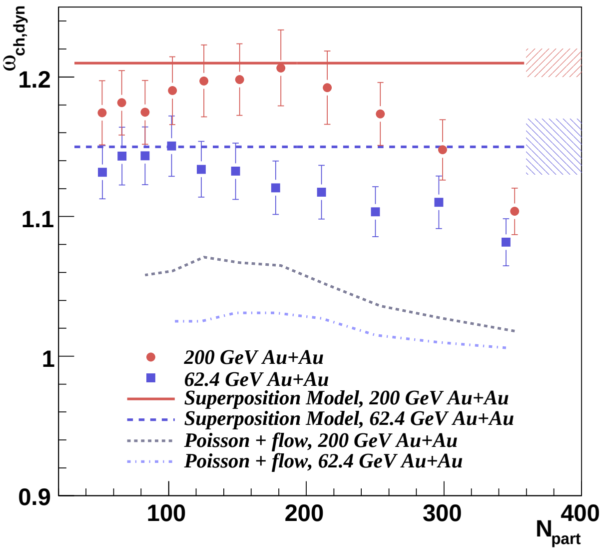

Fig. 1. Multiplicity fluctuations as a function of $N_{\rm part}$ for Au+Au collisions for $0.2 < p_{\rm T} < 2.0\,{\rm GeV}/c$. Contributions from impact parameter fluctuations have been removed. Shaded regions represent a 1σ range of the superposition model prediction derived from $p+p$ data.

where the hard scattering contribution is expected to be small. All of the data points are consistent with or below the participant superposition model estimate. This suggests that the data do not show any indications of the presence of a critical point, where the fluctuations are expected to be much larger than the participant superposition model expectation.

PHENIX has also completed a survey that expands upon previous measurements of event-by-event transverse momentum fluctuations [9]. The magnitude of the $p_{\rm T}$ fluctuations are measured using the variable $\Sigma_{p_{\rm T}}$, as described in [10]. $\Sigma_{p_{\rm T}}$ is the mean of the covariance of all particle pairs in an event, normalized by the inclusive mean $p_{\rm T}$. $\Sigma_{p_{\rm T}}$ is related to the inverse of the heat capacity of the system [11], which diverges with a power law behavior near the critical point: $C_V \propto \varepsilon^{-\alpha}$. The magnitude of $\Sigma_{p_{\rm T}}$ exhibits little variation for the different collision energies and does not scale with the jet cross section at different energies, hence hard processes are not the primary contributor to the observed fluctuations. Simulations show that elliptic flow contributes little [9]. With the exception of the most peripheral collisions, all systems exhibit a universal power law scaling as a function of $N_{\rm part}$. The data points for all systems are best described by the curve: $\Sigma_{p_{\rm T}} \propto N_{\rm part}^{-1.02\pm0.10}$. The observed scaling is independent of the $p_{\rm T}$ range over which the measurement is made.

PHENIX has studied identified particle fluctuations by measuring the event-by-event fluctuations of kaons to pions and protons to pions. One advantage of particle ratio measurements is that contributions from volume fluctuations cancel. Measurements are quoted in the variable $\nu_{\rm dyn}$:

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

If only random fluctuations are present, $\nu_{\rm dyn}$ is zero. Also, $\nu_{\rm dyn}$ is independent of acceptance.

The measurements for $\nu_{\rm dyn}(K,\pi)$ for $0.34 < p_{\rm T} < 1.05$ GeV/c are shown in Fig. 2. As with the $p_{\rm T}$ fluctuations, the fluctuations in $\langle K\rangle/\langle\pi\rangle$ demonstrate a $1/N_{\rm part}$ dependence. This is not seen in fluctuations of $\langle p\rangle/\langle\pi\rangle$, which are about an order of magnitude smaller and instead rise as centrality increases.

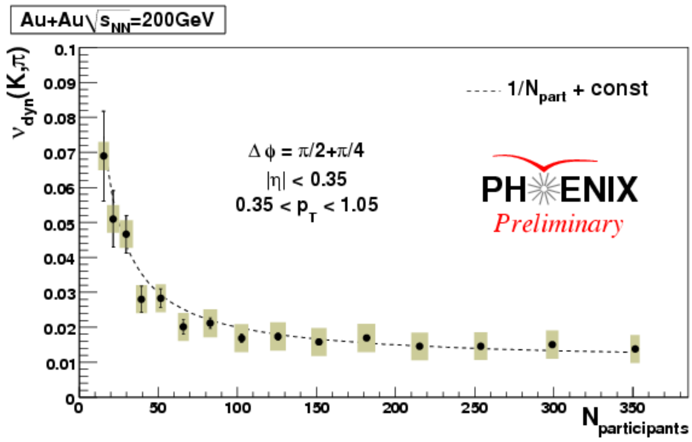

Fig. 2. Event-by-event fluctuations of the kaon-to-pion ratio for inclusive charged hadrons within the PHENIX acceptance in the transverse momentum range $0.35 < p_{\rm T} < 1.05$ GeV/c. The dashed line is a fit to the function $N_{\rm part}^{-1}$+const.

3. Azimuthal correlations at low transverse momentum

Near the critical point, correlation functions are also expected to be described by a power law function with exponent η. In the case of azimuthal correlation functions, the power law function is $C(\Delta\phi) \propto \Delta\phi^{-(d-2+\eta)}$, where d is the dimensionality of the system [2]. PHENIX has measured azimuthal correlation functions of like-sign pairs at low $p_{\rm T}$ for several collision systems. The correlations isolate the HBT peak in pseudorapidity by restricting $|\Delta\eta| < 0.1$ for each particle pair. Correlations are constructed for low

$p_{\rm T}$ pairs by correlating all particle pairs in an event where both particles lie within the $p_{\rm T}$ range $0.2 < p_{\rm T,1} < 0.4$ GeV/c and $0.2 < p_{\rm T,2} < 0.4$ GeV/c. Note that there is no trigger particle in this analysis. The correlation functions are constructed using mixed events as follows: $C(\Delta\phi) = \frac{dN/d\phi_{\rm data}}{dN/d\phi_{\rm mixed}} \frac{N_{\rm events,mixed}}{N_{\rm events,data}}$. Confirmation of the HBT peak has been made by observing its disappearance in unlike-sign pair correlations and by observing $Q_{\rm invariant}$ peaks when selecting this region.

For all collision systems, including 200 GeV $d+$ Au, the extracted value of the exponent η is shown in Fig. 3. The value of η lies between -0.6 and -0.7 with $d = 3$, independent of centrality. Since η is constant in heavy ion collisions, does not differ from the $d+$ Au system, and has a value that significantly differs from expectations from a QCD phase transition (*e.g.* if QCD belongs in the same universality class as the $3-D$ Ising model ($d = 3$), $\eta = +0.5$ [12]), it is unlikely that critical behavior is being observed in the correlation functions measured thus far.

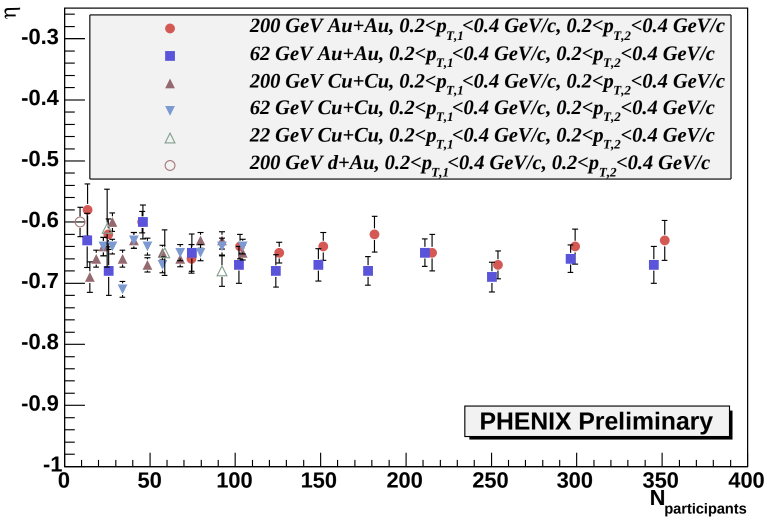

Fig. 3. The exponent η with $d = 3$ extracted from the like-sign correlation functions as a function of $N_{\rm part}$.

4. Conclusions

The fluctuation and correlation measures presented here do not provide a significant indication of the existence of a critical point or phase transition. This does not rule out the possibility that the critical point exists. Further searches will be facilitated by the upcoming RHIC low energy program.

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