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Beam-energy and system-size dependence of dynamical net charge fluctuations

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We present measurements of net charge fluctuations in Au + Au collisions at $\sqrt{s_{NN}} = 19.6$, 62.4, 130, and 200 GeV, Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV, and $p + p$ collisions at $\sqrt{s} = 200$ GeV using the dynamical net charge fluctuations measure $\nu_{+-,\mathrm{dyn}}$. We observe that the dynamical fluctuations are nonzero at all energies and exhibit a modest dependence on beam energy. A weak system size dependence is also observed. We examine the collision centrality dependence of the net charge fluctuations and find that dynamical net charge fluctuations violate $1/N_{\mathrm{ch}}$ scaling but display approximate $1/N_{\mathrm{part}}$ scaling. We also study the azimuthal and rapidity dependence of the net charge correlation strength and observe strong dependence on the azimuthal angular range and pseudorapidity widths integrated to measure the correlation.

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I. INTRODUCTION

Anomalous transverse momentum and net charge event-by-event fluctuations have been proposed as indicators of the formation of a quark-gluon plasma (QGP) in the midst of high-energy heavy ion collisions. A number of authors [1–3] have argued that entropy conserving hadronization of a plasma of quarks and gluons should produce a final state characterized by a dramatic reduction of the net charge fluctuations relative to that of a hadron gas. Simply put, their prediction relies on the notion that quark-quark correlations can be neglected, and hadronization of gluons produces pairs of positive and negative particles not contributing to the net charge fluctuations. Accounting for the fractional charge of the quarks, they find that for a QGP, the variance of the ratio of positive and negative particles scaled by the total charged particle multiplicity, a quantity they call D, should be approximately four times smaller than for a gas of hadron. Quark-quark correlations, however, may not be negligible; Koch *et al.* [1] extended their original estimates to include susceptibilities calculated on the lattice. They find that the quantity $D = 4\langle\Delta Q^2\rangle/N_{\rm ch}$ (where, ΔQ^2 is the variance of the net charge, $Q = N^+ - N^-$, and $N_{\rm ch}$ is the total number of charged particles observed in the particular momentum space window under consideration) is quantitatively different from their first basic estimate but nonetheless still dramatically smaller than values expected for a hadron gas. It is clear, however, that hadron collisions, and in particular heavy ion collisions, produce a substantial number of high mass particles and specifically short-lived (neutral) particles or resonances which decay into pairs of positive and negative particles. Such decays increase the multiplicity of charged particles in the final state while producing negligible impact on the net charge variance. Jeon and Koch have in fact argued that one can use the magnitude of net charge fluctuations to estimate the relative production of ρ and ω mesons [4]. Calculations based on a thermal model lead to a value D of order of 2.8, which, although reduced relative to the value expected for a pion gas, is nonetheless remarkably larger than that predicted for a QGP [1]. Note that transport models such as UrQMD predict values in qualitative agreement with those of thermal models [5]. A measurement of net charge fluctuations therefore appears, on the outset, as an interesting means of identifying the formation of quark-gluon plasma in high-energy heavy ion collisions.

The first measurements of net charge fluctuations were reported by both PHENIX [6] and STAR [7] Collaborations on the basis of Au + Au data acquired during the first run of the BNL Relativistic Heavy Ion Collider (RHIC) at $\sqrt{s_{NN}} =$ 130 GeV. Measurements were reported by PHENIX [6] in terms of a reduced variance, $\omega_Q = \langle\Delta Q^2\rangle/N_{\rm ch}$. Unfortunately, measured values of this quantity depend on the efficiency. STAR instead reported results [7,8] in terms of a dynamical net charge fluctuations measure, $\nu_{+-,{\rm dyn}}$, which is found to be a robust observable i.e., independent of detection efficiency. $\nu_{+-,{\rm dyn}}$ is defined by the expression

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

where $N_\pm$ are the number of positively and negatively charged particles in the acceptance of interest. Note that a simple relationship exists between ω_Q and $\nu_{+-,{\rm dyn}}$ written $\nu_{+-,{\rm dyn}} = 4(\omega_Q - 1)/N_{\rm ch}$. This relationship is applicable only if ω_Q is corrected for finite detection effects. Because such corrections are not trivial, we favor the use of $\nu_{+-,{\rm dyn}}$. We note additionally that both ω_Q (corrected for efficiency) and $\nu_{+-,{\rm dyn}}$ may be expressed (at least approximately) in terms of the variable $D \sim N_{\rm ch}\langle\Delta R^2\rangle$ (with $R = N_+/N_-$) used by Koch *et al.* [1] for their various predictions. Their use, for experimental measurements, avoid pitfalls associated with measurements of average values of the ratio, R, of particle multiplicities, where the denominator N_- may be small or even zero [6]. The measurements performed by the STAR [7] and PHENIX [6] Collaborations showed that the dynamical net charge fluctuations in Au + Au at $\sqrt{s_{NN}} = 130$ GeV are finite but small relative to the predictions by Koch *et al.* [1] for a QGP. The magnitude of the net charge fluctuations was found to be in qualitative agreement with HIJING predictions [9], although the data exhibit centrality dependence not reproduced within the HIJING calculations. Measured values also qualitatively agree with predictions by Bialas for quark coalescence [10] and Koch *et al.* for a resonance gas [1].

The scenario for dramatically reduced fluctuations as evidence for the formation of QGP is clearly excluded by the data at 130 GeV. However, in light of predictions of a tricritical point of the equation of state in the range $10 \leqslant \sqrt{s_{NN}} \leqslant$ 60 GeV [11,12], one might argue that the reduction of fluctuation might be larger at lower beam energies. Conversely, one may also argue that the volume of QGP formed in Au + Au collisions might increase at higher beam energies leading to reduced fluctuations at higher beam energy instead. One is thus led to wonder whether the fluctuations may be found to vary with beam energy thereby indicating the production of QGP above a critical threshold, or with progressively increasing probability at higher energies. In this paper, we consider this possibility by investigating how the strength of the dynamical net charge fluctuations varies with beam energy and system size in Au + Au and Cu + Cu collisions ranging in center-of-mass energy from the highest energy available at the CERN Super Proton Synchrotron (SPS) to the highest RHIC energy, and relative to $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. This analysis presents new information that may shed light on collision dynamics, e.g., in assessing the importance of collective effects and determining whether the gluon content information survives hadronization.

Various issues complicate the measurement and interpretation of net charge fluctuations. First, one must acknowledge that particle final state systems produced in heavy ion collisions although large, are nonetheless finite and therefore subject to charge conservation effects. Produced particles are also measured in a finite detector acceptance. Second, one may question whether the dynamical net charge fluctuations produced within the QGP phase may survive the hadronization process [13]. Shuryak and Stephanov [14] have argued that based on solutions of the diffusion equation within the context of a model involving Bjorken boost invariance, diffusion in rapidity space considerably increases the net charge fluctuations. They further argued that the reduced fluctuations predicted for a QGP might be observable only if fluctuations are measured over a very large rapidity range (of order of four units of rapidity). Unfortunately, charge conservation effects increase with the rapidity range considered and might become dominant for rapidity ranges of four units or more. Abdel-Aziz and Gavin [15], however, argued that the classical diffusion equation yields nonphysical solutions in the context of relativistic heavy ion collisions. They proposed a causal diffusion equation as a substitute of the classical diffusion equation for studies of net charge fluctuation dissipation. They found that causality substantially limits the extent to which diffusion can dissipate these fluctuations.

Third, there exists the possibility that the treatment by Koch *et al.* [1] of quark and gluons behaving as independent particles carrying full entropy may be inappropriate. Consider for instance that recent measurements of elliptical anisotropy of particle emission in Au + Au collisions show that meson and baryon elliptical flow, v_2, scales in proportion to the number of constituent quarks for transverse momenta in the range 1–4 GeV/c, thereby suggesting that hadrons are produced relatively early in the collisions through "coalescence" or recombination of constituent quarks. In a constituent quark scenario, the role of gluons in particle production is reduced. Relatively smaller charged particle multiplicities are therefore expected, and net charge fluctuations are correspondingly larger. Bialas [10] conducted a simple estimate of such a scenario, and reported net charge fluctuations D may be of order 3.3. Interestingly, this estimate suggests that fluctuations might be even larger than that expected for a resonance gas and as such should also be identifiable experimentally.

Theoretical estimates of the effect of hadronization on net charge fluctuation have been for the most part restricted to studies of the role of resonances, diffusion [14–16], and thermalization [17,18]. However, the collective motion of produced particles is clearly demonstrated in relativistic heavy ion collisions. Voloshin pointed out [19] that induced radial flow of particles produced in parton-parton collisions at finite radii in nucleus-nucleus collisions generate momentum-position correlations not present in elementary proton-proton collisions. Specifically, the effect of radial flow is to induce azimuthal correlations and to modify particle correlation strengths in the longitudinal direction. Voloshin showed that two-particle momentum correlations $\langle \Delta p_{T1}, \Delta p_{T2} \rangle$ are in fact sensitive to radial velocity profile as well as the average flow velocity. While one may not intuitively expect net charge fluctuations to exhibit a dramatic dependence on radial flow, simulations based on a simple multinomial particle production model including resonances such as the $\rho(770)$ indicate that net charge correlations are in fact also sensitive to radial flow through azimuthal net charge correlations [20]. They may as such be used to complement estimates of radial velocity obtained from fits of single-particle spectra with blast-wave parametrization or similar phenomenologies.

Measurements of charged particle fluctuations have also been proposed as a tool for discriminating between predictions of various microscopic models of nuclear collisions. Zhang *et al.* [21] found that measurements of dynamical fluctuations should exhibit sensitivity to rescattering effects based on calculations without rescattering with models VNIb [22] and RQMD [23]. They also found that models VNIb, HIJING [9], HIJING/BB [24], and RQMD predict qualitatively different dependencies on collision centrality. Similar conclusions were obtained by Abdel-Aziz [25].

Bopp and Ranft [26] compared predictions of net charge fluctuations (at midrapidities) by the dual parton model and statistical (thermal) models and found significant differences in the dispersion of the charges predicted by these models. They hence argued that charged particle fluctuations should provide a clear signal of the dynamics of heavy ion processes and enable a direct measurement of the degree of thermalization reached in heavy ion collisions. Gavin [17,18] similarly argued, based on PHENIX [6,27] and STAR [7,28] data, that measured transverse momentum and net charge fluctuations indeed present evidence for thermalization at RHIC.

In this work, we present measurements of dynamical net charge fluctuations in Au + Au collisions at $\sqrt{s_{NN}} =$ 19.6, 62.4, 130, and 200 GeV, Cu + Cu collisions at $\sqrt{s_{NN}} =$ 62.4 and 200 GeV, and $p + p$ collisions at $\sqrt{s} = 200$ GeV. We study the beam energy, system size, and collision centrality dependencies quantitatively in order to identify possible signature of the formation of a QGP. Some of the results presented in this work have been reported as preliminary data at various conferences [20]. The paper is organized into sections on the experimental method, results, systematic uncertainty studies, and conclusions.

II. EXPERIMENTAL METHOD

Our study of dynamical net charge fluctuations dependence on the beam energy is based on the observable $\nu_{+-,\mathrm{dyn}}$ used in the first STAR measurement [7]. The definition of $\nu_{+-,\mathrm{dyn}}$, its properties, and relationships to other measures of event-by-event net charge fluctuations were motivated and presented in detail in Refs. [8,29]. The authors showed $\nu_{+-,\mathrm{dyn}}$ is a robust observable. Robust is defined as indicating the observable is minimally affected by detector efficiency. The robustness of $\nu_{+-,\mathrm{dyn}}$ as an experimental observable was also discussed on the basis of Monte Carlo toy models by Nystrand *et al.* [30]; the authors verified explicitly with simple Monte Carlo generators that $\nu_{+-,\mathrm{dyn}}$ is insensitive to the details of the detector response and efficiency. Indeed, they verified that values of $\nu_{+-,\mathrm{dyn}}$ are independent of the track detection efficiency when the efficiency is uniform over the measured kinematic range. If the efficiency is not perfectly uniform across the acceptance, the robustness of $\nu_{+-,\mathrm{dyn}}$ is reduced in principle. However, in this work, the acceptance of the measurement is limited to a kinematic range where the efficiency is essentially uniform, and such effects are, therefore, negligible.

We here briefly review the definition and essential properties of this observable. Rather than measuring the event-by-event fluctuations of the ratio of positive and negative particle multiplicities (in a given acceptance), one considers the second moment of the difference between the relative multiplicities $N_+/\langle N_+\rangle$ and $N_-/\langle N_-\rangle$ as follows:

$$\nu_{+-} = \left\langle \left(\frac{N_+}{\langle N_+\rangle} - \frac{N_-}{\langle N_-\rangle} \right)^2 \right\rangle. \quad (2)$$

The Poisson limit, $\nu_{+-,\mathrm{stat}}$ of this quantity is equal to

$$\nu_{+-,\mathrm{stat}} = \frac{1}{\langle N_+\rangle} + \frac{1}{\langle N_-\rangle} \quad (3)$$

The "nonstatistical" or "dynamical" fluctuations can thus be expressed as the difference between the above two quantities:

$$\nu_{+-,\mathrm{dyn}} = \nu_{+-} - \nu_{+-,\mathrm{stat}} = \frac{\langle N_+(N_+ - 1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_- - 1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+ N_-\rangle}{\langle N_-\rangle\langle N_+\rangle}. \quad (4)$$

From a theoretical standpoint, $\nu_{+-,\mathrm{dyn}}$ can be expressed in terms of two-particle integral correlation functions as $\nu_{+-,\mathrm{dyn}} = R_{++} + R_{--} - 2R_{+-}$, where the terms $R_{\alpha\beta}$ are ratios of integrals of two- and single-particle pseudorapidity density functions defined as

$$R_{\alpha\beta} = \frac{\int d\eta_\alpha d\eta_\beta \frac{dN}{d\eta_\alpha d\eta_\beta}}{\int d\eta_\alpha \frac{dN}{d\eta_\alpha} \int d\eta_\beta \frac{dN}{d\eta_\beta}} - 1. \quad (5)$$

The dynamical net charge fluctuations variable $\nu_{+-,\mathrm{dyn}}$ is thus basically a measure of the relative correlation strength of $++$, $--$, and $+-$ particle pairs. Note that by construction, these correlations are identically zero for Poissonian or independent particle production. In practice, however, produced particles are partly correlated, through the production of resonances, string fragmentation, jet fragmentation, or other mechanisms. The relative and absolute strengths of R_{++}, R_{--}, and R_{+-} may vary with colliding systems and beam energy. In addition, by virtue of charge conservation, the production of $+-$ pairs is expected to be more strongly correlated than the production of $++$ or $--$ pairs. For this reason, it is reasonable to expect R_{+-} to be larger than R_{++} or R_{--}. In fact, one finds experimentally that $2R_{+-}$ is actually larger than the sum $R_{++} + R_{--}$ in $p + p$ and $p + \overline{p}$ collisions measured at the CERN Intersecting Storage Rings and Fermi National Accelerator Laboratory [31,32]. Measurements of $\nu_{+-,\mathrm{dyn}}$ are thus expected and have indeed been found to yield negative values in nucleus-nucleus collisions as well [7].

We also note $\nu_{+-,\mathrm{dyn}}$ is essentially a measure of the variance of $N_+ - N_-$. This difference is "orthogonal" to the multiplicity $N_+ + N_-$, and thus linearly independent. There is, therefore, no bias introduced by binning $\nu_{+-,\mathrm{dyn}}$ measurements on the basis of the reference multiplicity (multiplicity within $|\eta| < 0.5$) as discussed below.

As a technical consideration, our study of the $\nu_{+-,\mathrm{dyn}}$ dependence on collision centrality is carried out in terms of charged particle multiplicity bins, as discussed in detail below. To avoid dependencies on the width of the bins, we first determine the values of dynamical fluctuation, $\nu_{+-,\mathrm{dyn}}(m)$, for each value of multiplicity m. The dynamical fluctuations are then averaged across the selected finite width of the centrality bins with weights corresponding to the relative cross section $p(m)$, measured at each value of multiplicity. For example, in the multiplicity range from m_{min} to m_{max}, we calculate the average as

$$\nu_{+-,\mathrm{dyn}}(m_{\mathrm{min}} \leqslant m < m_{\mathrm{max}}) = \frac{\sum \nu_{+-,\mathrm{dyn}}(m)p(m)}{\sum p(m)}. \quad (6)$$

This study is based on the notion that if Au + Au collisions (or any other $A + A$ system) trivially consist of a superposition of independent nucleon-nucleon collisions, with no rescattering of the produced secondaries, then $\nu_{+-,\mathrm{dyn}}$ is expected to scale inversely to the number of participating nucleons and the number of charged particles or, more appropriately, the number of actual nucleon+nucleon collisions. One can thus infer that the quantity $|\nu_{+-,\mathrm{dyn}}\, dN_{\mathrm{ch}}/d\eta|$ should be independent of collision centrality under such a scenario. We shall therefore examine whether indeed the dynamical net charge fluctuations scale with the number of participants or with the invariant multiplicity.

The data used in this analysis were measured using the solenoidal tracker at RHIC (STAR) detector during the 2001, 2002, 2004, and 2005 data RHIC runs at Brookhaven National Laboratory. They include Au + Au collisions data collected at $\sqrt{s_{NN}} = 19.6$, 62.4, 130, and 200 GeV, Cu + Cu collisions data at $\sqrt{s_{NN}} = 62.4$ and 200 GeV, and $p + p$ collisions data measured at $\sqrt{s} = 200$ GeV. For the Au + Au and Cu + Cu collisions, all but the 19.6 GeV data were acquired with minimum bias triggers by requiring a coincidence of two zero degree calorimeters (ZDCs) located at 18 m from the center of the interaction region on either side of the STAR detector. For the 19.6 GeV data, a combination of minimum bias and central triggers was used. The centrality trigger was achieved using a set of scintillation detectors, called the central trigger barrel (CTB) surrounding the main time projection chamber (TPC). Technical descriptions of the STAR detector and its components are published in technical reports [33,34]. For $p + p$ collisions, a minimum bias trigger was used based on the CTB detector. The analysis carried out in this work is rather similar to that published in the first net charge fluctuation measurement [7].

This analysis is based on charged particle track reconstruction measurements performed with the STAR TPC. The TPC is located in a large solenoidal magnetic field producing a uniform axial magnetic field. The magnetic field was set to 0.25 T for Au + Au collisions at $\sqrt{s_{NN}} = 19.6$ and 130 GeV data, and 0.5 T for Au + Au and Cu + Cu collisions at 62.4 and 200 GeV data. The increased magnetic field results in a slight reduction of the detection efficiency for charged particle tracks with transverse momenta below 0.2 GeV/c and a modest improvement in momentum resolution. This analysis used tracks from the TPC with transverse momentum in the range $0.2 < p_T < 5.0$ GeV/c with pseudorapidity $|\eta| < 0.5$. Systematic effects associated with finite thresholds and momentum-dependent efficiency are discussed in Sec. IV.

To limit the net charge fluctuations analysis to primary charged particle tracks only (i.e., particles produced by the collision), tracks were selected on the basis of their distance of closest approach (DCA) to the collision vertex. DCA is defined as the distance between the track and the primary vertex position. A nominal cut of DCA < 3 cm was used for results presented in this paper. Systematic effects associated with this cut are discussed in Sec. IV.

Events were selected for analysis if their collision vertices lay within a maximum distance from the center of the TPC and they passed a minimum track multiplicity cut (see below). The vertex position was determined using a fit involving all found tracks. The maximum distance along the beam axis from the center of the TPC (also called the z vertex cut) was set to 75 cm for the Au + Au 19.6 and 130 GeV data, further restricted to 25 cm for 62.4 and 200 GeV data. However, a z vertex cut of 30 cm was used in Cu + Cu 62.4 and 200 GeV data. A maximum of 75 cm was used for the $p + p$ data. The wide 75 cm cut was used to maximize the event sample used in this analysis. The observable $\nu_{+-,\mathrm{dyn}}$ measured in this analysis (as described below) is a robust experimental variable, and is by construction largely insensitive to restricted detection efficiencies provided those efficiencies do not vary dramatically across the detector acceptance. We indeed find that as long as the longitudinal cut is limited to values below 75 cm, for which the track detection efficiency is rather insensitive to the pseudorapidity of the track, the measured values of $\nu_{+-,\mathrm{dyn}}$ are invariant within the statistical uncertainties of the $p + p$ measurements. The detection efficiency is approximately constant in the range $|\eta| < 1.0$ for $|z| < 30$ and drops to zero for $|\eta| > 1.0$. For $30 < |z| < 75$ the efficiency at $|\eta| \approx 1$ is reduced by a few percent. This dependence on the z vertex causes a few percent systematic deviation on $\nu_{+-,\mathrm{dyn}}$. The analyses reported in this paper are based on 1×10^5, 1×10^6, 1.44×10^5, and 1×10^7 Au + Au events at 19.6, 62, 130, and 200 GeV, respectively; 9×10^6 and 5.5×10^6 Cu + Cu events at 62 and 200 GeV; and 2.7×10^6 $p + p$ events.

The magnitude of net charge fluctuations is quite obviously subject to change with the total multiplicity of produced charged particles. It is thus necessary to measure the magnitude of the fluctuations and correlations as a function of the collision centrality. Measurements at the BNL Alternating Gradient Synchrotron (AGS), SPS, and RHIC have shown that there is a strong anticorrelation between the number of collision spectators (i.e., projectile/target nucleons undergoing little or no interaction with target/projectile nucleons) and the multiplicity of charged particles produced in the collisions. We use the standard collision centrality definition used in other STAR analyses and base estimates of the collision centrality on the uncorrected multiplicity of charged particle tracks measured within the TPC in the pseudorapidity range $-0.5 < \eta < 0.5$. While low multiplicity events correspond to peripheral (large impact parameter) collisions, high multiplicities are associated with central (small impact parameter) collisions. The pseudorapidity range $-0.5 < \eta < 0.5$ is used for collision centrality estimates, rather than the full range $-1.0 < \eta < 1.0$ in principle measurable with the TPC, to minimize effects of detector acceptance and efficiency on the collision centrality determination. With the narrow cut $-0.5 < \eta < 0.5$, the track detection efficiency is rather insensitive to the position of the collision vertex (along the beam direction) in the range $-75 < z < 75$ cm used in the analysis of Au + Au at $\sqrt{s_{NN}} = 130$ GeV data, and centrality selection biases are thus negligible. The efficiency for tracks with $0.5 < \eta < 1$ on the other hand drops markedly for vertex positions $|z| > 50$ cm. Although the analysis of Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV data were conducted with the narrower $|z| < 25$ cm and $|z| < 30$ cm range, respectively, enabled by the more compact interaction region delivered by the accelerator during these runs, the centrality determination was estimated on the basis of the same pseudorapidity range in order to provide uniform and consistent centrality cuts.

The centrality bins were calculated as a fraction of this multiplicity distribution starting at the highest multiplicities. The ranges used were 0–5% (most central collisions), 5–10%, 10–20%, 20–30%, 30–40%, 40–50%, 50–60%, 60–70%, and 70–80% (most peripheral) for Au + Au collisions. Similarly, collision centrality slices used in Cu + Cu collisions are 0–10% (most central), 10–20%, 20–30%, 30–40%, 40–50% and 50–60% (most peripheral). Each centrality bin is associated with an average number of participating nucleons, N_{part}, using the Glauber Monte Carlo calculation [35]. At low multiplicities, the finite detector acceptance and track detection efficiencies imply that estimates of the collision centrality are subject to large errors.

Events are included or "counted" in this analysis provided a collision vertex is found (as per the discussion of the previous paragraphs) and at least one particle is found in the range $-0.5 < \eta < 0.5$. While event counting efficiencies are essentially unity for large multiplicity collisions, they are limited ($<$1) for small multiplicities corresponding to most peripheral collisions. The limited efficiency stems from finite track and vertex finding efficiencies. Track finding efficiency within the TPC was studied through detailed Monte Carlo simulations of the detector response with track embedding. For minimal track quality cuts such as those used in this analysis, one finds the track finding efficiency is about 95% for $p_T > 0.2$ GeV/c in peripheral collisions. It reduces to approximately 85% for most central collisions and falls to zero for primary tracks with $p_T < 0.1$ GeV/c. The efficiencies of positive and negative particles are found to be the same within the statistical uncertainties. The data shown were integrated for tracks with $0.2 < p_T < 5.0$ GeV/c, $|\eta| < 0.5$, and $0 < \phi < 2\pi$. Note that the minimum p_T cut used in this new analysis is different than that used in the first reported study [7]. A value of 0.2 GeV/c is used for all measured beam energies and field settings to avoid systematic effects associated with p_T dependent detection efficiency below 0.2 GeV/c. The results presented in this work for 130 GeV are nonetheless in agreement with results reported by STAR in the first measurement of net charge fluctuations in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV [7].

Simulations reveal that the vertex finding efficiency is maximum for total charged particle multiplicity of order 5 and greater in the TPC. We studied the event counting efficiency of this analysis with a simple simulation based on events generated with the HIJING model [36] and found that the event counting efficiency is maximum for produced charged particle multiplicities (in the range $-0.5 < \eta < 0.5$) exceeding 12. The vertex counting efficiency is around 90% for multiplicities larger than 5 and falls abruptly to zero for smaller values. For this reason, the analysis presented in this work is limited to reference multiplicities in excess of 10 and 17 for Au + Au and Cu + Cu collisions where it is deemed minimally biased or unbiased.

To eliminate track splitting, we restricted our analysis to charged particle tracks producing a number of fit hits amounting to 52% of the number of possible hits determined by the track geometry and the detector acceptance. This cut

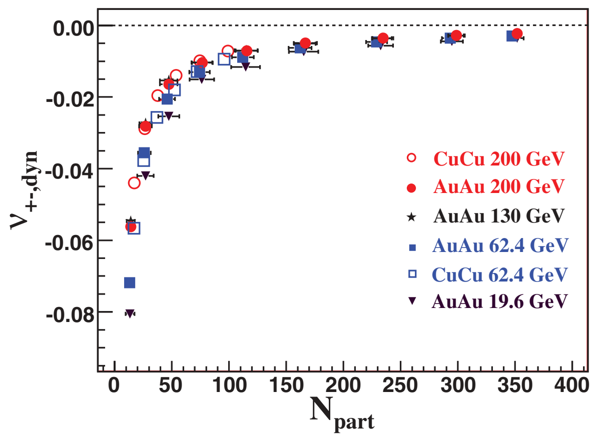

FIG. 1. (Color online) Dynamical net charge fluctuations, $\nu_{+-,\text{dyn}}$, of particles produced within pseudorapidity $|\eta| < 0.5$, as function of the number of participating nucleons.

equally reduces the number of positive and negative tracks by a few percent only.

III. NET CHARGE FLUCTUATION RESULTS

We present, in Fig. 1, measurements of the dynamical net charge fluctuations, $\nu_{+-,\text{dyn}}$, as a function of collision centrality in Au + Au collisions at $\sqrt{s_{NN}} = 19.6, 62.4, 130$, and 200 GeV, and Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV.

In Fig. 1, we see that the dynamical net charge fluctuations, in general, exhibit a monotonic dependence on the number of participating nucleons. At a given number of participants, the measured fluctuations also exhibit a modest dependence on beam energy, with the $\nu_{+-,\text{dyn}}$ magnitude being the largest in Au + Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV. The $\nu_{+-,\text{dyn}}$ values measured for $p + p$ collisions at $\sqrt{s} = 200$ GeV amount to -0.230 ± 0.019(stat).

We first discuss the energy dependence of the fluctuations. The collision centrality dependence is addressed in the following section.

A. Beam energy and size dependence

A study of the net charge fluctuation dependence on the beam energy is of interest given that it can potentially reveal a change in the magnitude of the fluctuations and signal the formation of QGP.

We conduct this study primarily on the basis of the 0–5% and 0–10% most central collisions in Au + Au and Cu + Cu collisions, respectively. Extensions to less central and peripheral collisions are possible but subject to additional uncertainties raised by small systematic uncertainties involved the collision centrality determination.

As already stated in the Introduction, charge conservation and the finite size of the colliding system intrinsically limit the magnitude of the net charge correlations. Intuitively, one expects charge conservation effects to become progressively smaller with increasing charged particle multiplicity. Charge conservation effects are nonetheless definite at all beam energies and produced multiplicities. Specifically, one estimates that charge conservation implies a minimum value of order $\nu_{+-,\text{dyn}} = -4/N_{4\pi}$, where $N_{4\pi}$ is the *total* charged particle multiplicity produced over 4π (see Ref. [29] for a derivation of this estimate). This estimate was obtained [29] assuming that charge conservation implies global correlations but no dependence of these correlations on rapidity. Therefore, charge conservation effects may be different than those estimated in this work. Nonetheless, for simplicity, we use the above expression to estimate the effects of charge conservation on the dynamical net charge fluctuations.

Corrections to $\nu_{+-,\text{dyn}}$ for system size and charge conservation require knowledge of the total charged particle multiplicity. Although, strictly speaking, no experiment at RHIC actually measures particle production with complete coverage, the PHOBOS experiment comes the closest with a rapidity coverage of $|\eta| < 5.4$ over 2π azimuthal angles and a minimum transverse momentum of order 100 MeV/c. PHOBOS has published data on total measured charged particle multiplicities of Au + Au collisions at $\sqrt{s_{NN}} =$ 19.6, 62.4, 130, and 200 GeV [37–42] and Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV [43]. We infer charged particle multiplicities for $p + p$ collisions at $\sqrt{s} = 200$ GeV based on charged particle multiplicity per participant reported by PHOBOS [44]. We correct for differences in collision centralities between the PHOBOS and STAR measurements using a linear interpolation based on the two most central bins measured by PHOBOS. The number of participating nucleons N_{part}, total multiplicities N_{ch}, and uncorrected and corrected values ($\nu^{\text{corr}}_{+-,\text{dyn}}$) of $\nu_{+-,\text{dyn}}$ are shown in Table I for $p + p$ collisions at $\sqrt{s} = 200$ GeV, all four energies in Au + Au collisions, and two energies in Cu + Cu collisions.

The $\nu^{\text{corr}}_{+-,\text{dyn}}$ values are shown in Fig. 2 as function of beam energy for 0–5% central Au + Au collisions with solid squares (in red color online) and for 0–10% central Cu + Cu collisions with solid circles (in black online). The displayed error bars include (a) the statistical errors involved in the measurement of $\nu_{+-,\text{dyn}}$ and (b) the total charged particle multiplicities. The boxes show our estimates of the systematic uncertainties involved in the measurements of both quantities. Data from this work are compared to corrected dynamical net charge fluctuations values by the PHENIX and CERES Collaborations. The PHENIX point (triangle, in blue color

TABLE I. Number of participating nucleons, total multiplicity, and uncorrected and corrected $\nu_{+-,\text{dyn}}$ values for $p + p$, Au + Au, and Cu + Cu collisions at the energies shown (in GeV).

System	Energy	N_{part}	N_{ch}	$\nu_{+-,\text{dyn}}$	$\nu^{\text{corr}}_{+-,\text{dyn}}$
$p + p$	200	2	22	−0.2301	−0.04407
Au + Au	200	351	5092	−0.0024	−0.00163
Au + Au	130	351	4196	−0.0021	−0.00121
Au + Au	62.4	348	2788	−0.0029	−0.00146
Au + Au	19.6	348	1683	−0.0035	−0.00113
Cu + Cu	200	98	1410	−0.0071	−0.00430
Cu + Cu	62.4	95	790	−0.0093	−0.00437

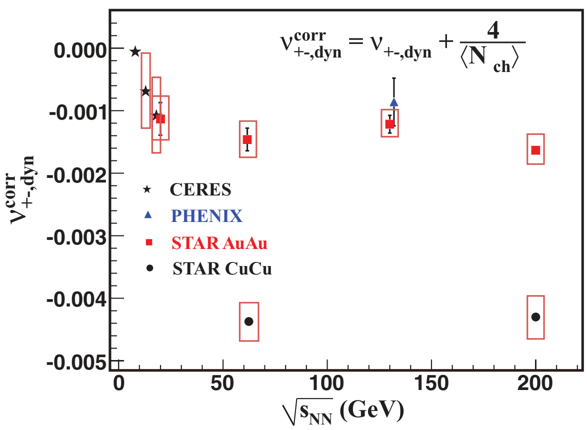

FIG. 2. (Color online) Corrected values of dynamical net charge fluctuations ($\nu^{corr}_{+-,dyn}$) measured in central collisions as a function of $\sqrt{s_{NN}}$. See text for details.

online) is calculated (as already discussed in Ref. [7]) from data published on the basis of the ω_Q observable [6] and corrections based on total multiplicities measured by PHOBOS (as per values shown in Table I). The CERES data points (star, in black online), obtained for Pb + Au collisions, are extracted from their published results [45]. They include estimates of the systematic uncertainties (open rectangles) as well as statistical uncertainties (solid lines).

We first note that the PHENIX and STAR points measured at 130 GeV are in quantitative agreement as already reported [7]. The large error bar associated with the PHENIX measurement stems mainly from systematic uncertainties associated with corrections for detection efficiencies [7]. We observe additionally that the STAR 19.6 GeV measurement agrees with a measurement by CERES at the same energy. The STAR measurements in Cu + Cu collisions show a sharp increase in magnitude. This difference could partly be attributed to the difference in the number of participating nucleons in Au + Au and Cu + Cu collisions at 0–5% and 0–10% centralities, respectively. However, the magnitude of corrected dynamical fluctuations in Cu + Cu collisions when scaled by the ratio of number of participants in Cu + Cu collisions to number of participants in Au + Au collisions is $-0.0009 \pm 2 \times 10^{-5}$(stat) $\pm$ 6×10^{-5}(sys) and $-0.001 \pm 2 \times 10^{-5}$(stat) $\pm 8 \times 10^{-5}$(sys) at $\sqrt{s_{NN}} = 62.4$ and 200 GeV, respectively. We also note that CERES reports a dramatic reduction in the magnitude of $\nu_{+-,dyn}$ at the lowest energy measured at SPS. We thus conclude that net charge fluctuations corrected for charge conservation show no obvious beam energy dependence in the range from 19.6 to 200 GeV. However, there is a clear system size dependence when comparing Au + Au and Cu + Cu collisions.

Below 19.6 GeV, there appears to be a decrease in the magnitude of $\nu^{corr}_{+-,dyn}$ at the lowest SPS energies. Difference between STAR and CERES results may in part stem from differences in pseudorapidity acceptance.

Measurements at the SPS have shown that particle production at 5 GeV and lower energies is dominated by baryons, while meson and resonance production become increasingly dominant at energies above 19.6 GeV. This suggests that the change in dynamical net charge fluctuations below 19.6 GeV might, in part, be due to this shift in particle production dominance. It is also conceivable that the differences between the values measured below and above 19.6 GeV may result from changes in the collision dynamics and final state interaction effects [11–18,25,26].

B. Collision centrality dependence

The observed monotonic reduction of the magnitude of $\nu_{+-,dyn}$ with increasing number of participants, seen in Fig. 1, arises principally from the progressive dilution of the two-particle correlation when the number of particle sources is increased. In fact, one expects $\nu_{+-,dyn}$ to be strictly inversely proportional to the number of participating nucleons or the produced particle multiplicity if Au + Au collisions actually involve mutually independent nucleon-nucleon interactions, and rescattering effects may be neglected.

We investigate the possibility of such a scenario by plotting the dynamical fluctuations scaled by the measured particle multiplicity density in pseudorapidity space ($dN_{ch}/d\eta$) in Fig. 3(a). Data from Au + Au collisions at various energies are shown with solid symbols, while data from Cu + Cu collisions at 62.4 and 200 GeV are shown with open symbols. Values of $dN_{ch}/d\eta$ used for the scaling correspond to efficiency corrected charged particle multiplicities measured by STAR [46] and PHOBOS [37–43]. We note that the correction applied in Sec. III A to account for charge conservation is useful in studying the energy dependence of the net charge fluctuations. Its use for centrality, pseudorapidity, and azimuthal dependencies, however, is not warranted given that insufficient data are available to reliably account for charge conservation effects. Also, the applied correction is model dependent, i.e., it assumes charge conservation applies only globally [29].

We note from Fig. 3(a) that the magnitude of $\nu_{+-,dyn}$ scaled by $dN_{ch}/d\eta$ for Au + Au 200 GeV data is different from the rest of the data. This could partly be attributed to the larger multiplicity produced in Au + Au 200 GeV. We additionally observe that all four distributions exhibit the same qualitative behavior: the amplitude $|\nu_{+-,dyn} dN_{ch}/d\eta|$ is smallest for peripheral collisions and increases monotonically by $\sim$40% in central collisions in Au + Au and Cu + Cu systems. The observed $|\nu_{+-,dyn}\, dN_{ch}/d\eta|$ increases with the increase in collision centrality. The dashed line in the figure corresponds to the charge conservation effect, and the solid line to the prediction for a resonance gas. The figure indicates that dynamical net charge fluctuations, scaled by $dN_{ch}/d\eta$, are rather large. Most central collisions in Au + Au 200 GeV approach the prediction for a resonance gas [1]. Indeed, observed values of $\nu_{+-,dyn}$ are inconsistent with those predicted based on hadronization model of Koch *et al.* [1–3]. Given recent observations of elliptic flow, suppression of particle production at high p_T ($R_{AA} \sim 0.2$), and two-particle correlation functions indicating the formation of a strongly interacting medium (sQGP) in $A + A$ collisions at RHIC energies, this suggests that the signal predicted by the authors [1–3] may be washed out by final state interactions, diffusion, expansion, collision

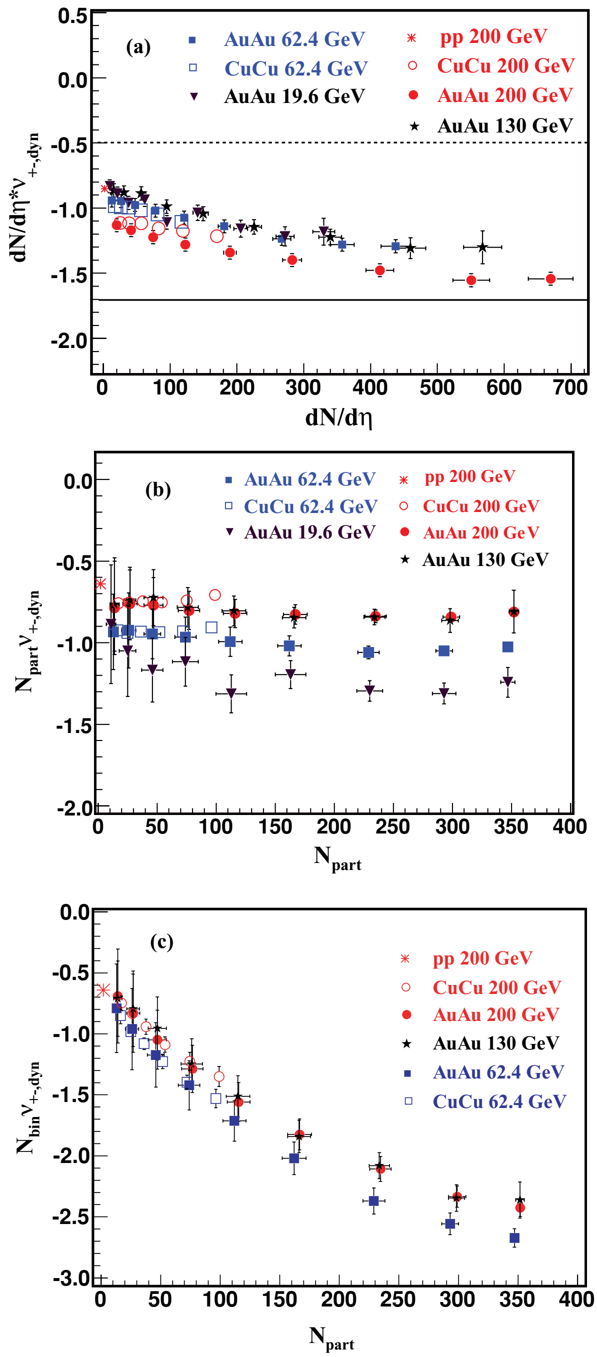

FIG. 3. (Color online) Dynamical net charge fluctuations $\nu_{+-,\mathrm{dyn}}$ of particles produced with pseudorapidity $|\eta| < 0.5$ scaled by (a) the multiplicity $dN_{\mathrm{ch}}/d\eta$, where the dashed line corresponds to charge conservation effect and the solid line to the prediction for a resonance gas, (b) the number of participants, and (c) the number of binary collisions.

dynamics, string fusion [47], or other effects [11–18,25,26,48], some of which were discussed in the Introduction.

Changes in the collision dynamics with increasing centrality are indicated by these data. Such a conclusion should perhaps not come as a surprise in view of the large elliptical flow and the significant reduction of particle production at high transverse momenta reported by all RHIC experiments [48].

We also note the PHOBOS Collaboration has reported that the charged particle multiplicity per participant nucleon pair rises substantially with increasing number of participants. They report a value of $dN_{\mathrm{ch}}/d\eta/(N_{\mathrm{part}}/2)$ of order 3.9 in central 200 GeV Au + Au collisions compared with a value of 2.5 in $p + p$ collisions at the same energy [39]. This amounts to a 56% increase, similar in magnitude to that of $|\nu_{+-,\mathrm{dyn}}\, dN_{\mathrm{ch}}/d\eta|$ measured in this work. We thus infer that much of the centrality dependence of $|\nu_{+-,\mathrm{dyn}}\, dN_{\mathrm{ch}}/d\eta|$ is due to the rise of $dN_{\mathrm{ch}}/d\eta/(N_{\mathrm{part}}/2)$ with increasing N_{part}.

To validate this assertion, we plot in Fig. 3(b) the dynamical fluctuation scaled by the number of participants, $N_{\mathrm{part}}\nu_{+-,\mathrm{dyn}}$ as a function of the number of participants. Vertical error bars represent statistical uncertainties. Values of $N_{\mathrm{part}}\nu_{+-,\mathrm{dyn}}$ exhibit a small dependence on the collision centrality at all four measured energies in Au + Au collisions and two energies in Cu + Cu collisions. The measured data scaled by the number of participants N_{part} are thus consistent with either no or a very weak centrality dependence. However, a definite energy dependence of $N_{\mathrm{part}}\nu_{+-,\mathrm{dyn}}$ is observed. We also scale $\nu_{+-,\mathrm{dyn}}$ with the number of binary collisions, shown in Fig. 3(c). While we observe that the datasets follow a common trend, $N_{\mathrm{bin}}\, \nu_{+-,\mathrm{dyn}}$ clearly exhibits dramatic collision centrality dependence. Such a dependence is, however, expected given that the measured dynamical net charge fluctuations are dominated by low momentum particles with large cross sections for which binary scaling does not apply. The statistical errors on $\nu_{+-,\mathrm{dyn}}$ and the scaling factors used in Figs. 3(a)–3(c) are added in quadrature.

C. Longitudinal and azimuthal dependencies of the dynamical fluctuations

Pratt *et al.* [49,50] have argued that the width of longitudinal charge balance functions should significantly narrow in central Au + Au collisions relative to peripheral collisions or $p + p$ collisions due to delayed hadronization following the formation of a QGP. STAR has in fact reported that, as predicted, a narrowing of the balance function does occur in central Au + Au collisions relative to peripheral collisions [51]. We note, however, as already pointed out by Pratt *et al.* and more recently by Voloshin [19], that radial flow produced in heavy ion collisions induces large position-momentum correlations which manifest themselves in angular, transverse momentum, and longitudinal two-particle correlations. The observed narrowing of the longitudinal charge balance function therefore cannot be solely ascribed to delayed hadronization. It is thus important to gauge the change in two-particle correlations imparted by radial flow effects. As a first step toward this goal, we present studies of the net charge fluctuation dependence on the integrated pseudorapidity and azimuthal ranges.

We plot in Fig. 4(a) values of $\nu_{+-,\mathrm{dyn}}(\eta)$ measured for different ranges of pseudorapidity η. To compare data measured at different centralities, beam energies, and system size, measured values are normalized by the magnitude of $\nu_{+-,\mathrm{dyn}}(\eta)$ for a pseudorapidity range $|\eta| < 1$ [$\nu_{+-,\mathrm{dyn}}(1)$]. The data shown in Fig. 4(a) are from Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV, Cu + Cu collisions at 62.4 and

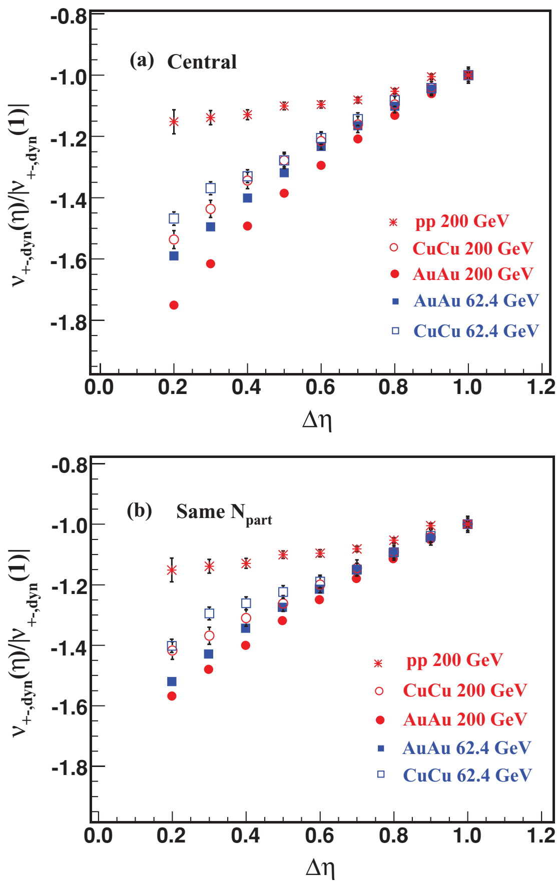

FIG. 4. (Color online) Dynamical fluctuations $\nu_{+-,\mathrm{dyn}}$, normalized to their value for $|\eta| < 1$, as function of the integrated pseudorapidity range. (a) Data for Au + Au collisions at $\sqrt{s_{NN}} = 62.4$, 200 GeV (0–5%) and for Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$, 200 GeV (0–10%) are compared with inclusive $p + p$ data at $\sqrt{s} = 200$ GeV. (b) Data for Au + Au collisions at $\sqrt{s_{NN}} = 62.4$, 200 GeV (30–40%) and for Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$, 200 GeV (0–10%) are compared with inclusive $p + p$ collision data at $\sqrt{s} = 200$ GeV.

200 GeV, and $p + p$ data obtained at 200 GeV. One finds the magnitude of the normalized correlation is maximum for the smallest pseudorapidity ranges and decreases monotonically to unity, at all energies and centralities, with increasing pseudorapidity range.

The dynamical fluctuations being essentially a measure of two-particle correlation dominated by the R_{+-} term, one finds, as expected, that the correlation is strongest for small rapidity intervals and is increasingly diluted for larger intervals. For example, in Cu + Cu collisions at $\sqrt{s_{NN}} =$ 200 GeV, the typical values of R_{++}, R_{--}, and R_{+-} are 0.99256, 0.992518, and 0.996099, respectively. One observes that the magnitudes of $|\nu_{+-,\mathrm{dyn}}(\eta)/\nu_{+-,\mathrm{dyn}}(1)|$ in Cu + Cu collisions at 62.4 and 200 GeV are quite different from Au + Au collisions at comparable energies. This shows that the collision dynamics in $p + p$ collisions, 0–10% Cu + Cu, and 0–5% Au + Au collisions are significantly different. Indeed, we find the relative magnitude of the correlations measured for $|\eta| < 0.5$ increases by nearly 25% for Au + Au 200 GeV relative to those in $p + p$. Note in particular that the slope ($d\nu_{+-,\mathrm{dyn}}/d\eta$) in $p + p$, Cu + Cu, and Au + Au systems depends on the correlation length (in pseudorapidity): the shorter the correlation, the larger the slope. The observed distributions then indicate that the correlation length is shorter for central collisions and for larger systems, in agreement with the observed reduction of the charge balance function [51]. The larger values of the slopes observed for most central collisions (as well as for larger systems) indicate that correlated pairs of negative/positive particles tend to be emitted closer in rapidity than those produced in peripheral Au + Au or $p + p$ collisions. Authors of Ref. [49] have proposed that a reduction of the width of the balance function and conversely a relative increase of short-range ($|\eta| < 0.5$) correlations could signal delayed hadronization. The observed increase in the correlation reported here might, however, also result from the strong radial flow believed to exist in central Au + Au collisions.

A comparison of Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV (30–40% central) is made with Cu + Cu collisions at the two energies for 0–10% centrality in Fig. 4(b), as these centralities correspond to approximately the same number of participant nucleons. We observe that the difference between the magnitudes of normalized correlations measured with the two colliding systems is smaller at an approximately equal number of participants than that observed in central collisions [Fig. 4(a)]. This suggests that the magnitude and width of the charge particle correlation depends primarily on the number of participants but less on the colliding systems. The difference between the two systems is, however, non null, and it may arise from fluctuations in the number of participants or minor differences in the collision dynamics.

To understand the role of radial flow in net charge fluctuations measured in a limited azimuthal range (i.e., less than 2π), first consider that the magnitude of $\nu_{+-,\mathrm{dyn}}$ is, in large part, determined by the abundance of neutral resonances, such as the $\rho(770)$. The decay of neutral resonances into pairs of charged particles increases the charged particle multiplicity without affecting the variance of the net charge. An increasing fraction of neutral resonances (relative to other particle production mechanisms) therefore leads to reduced magnitude of $\nu_{+-,\mathrm{dyn}}$. Consider additionally that large radial flow velocity should lead to a kinematic focusing of the decay products in a narrow cone. The opening angle of the cone will decrease with increasing radial velocity boost. One thus expects that while measuring $\nu_{+-,\mathrm{dyn}}$ in a small azimuthal wedge, one should have greater sensitivity to the level of kinematic focusing, i.e., the magnitude of the dynamical net charge fluctuation (correlation) should increase with the magnitude of the radial flow velocity. Azimuthal net charge correlations should therefore be rather sensitive to the magnitude of the radial flow velocity.

Figures 5(a) and 5(b) display azimuthal net charge correlations integrated over azimuthal angle ranges from 10° to 360° for Au + Au and Cu + Cu collisions at 200 GeV. An azimuthal wedge of, for example, 90° would divide the complete phase space into four sectors, where we denote each sector as a bin. The figure shows results from nine azimuthal wedges obtained after averaging $\nu_{+-,\mathrm{dyn}}$ values for all bins in each

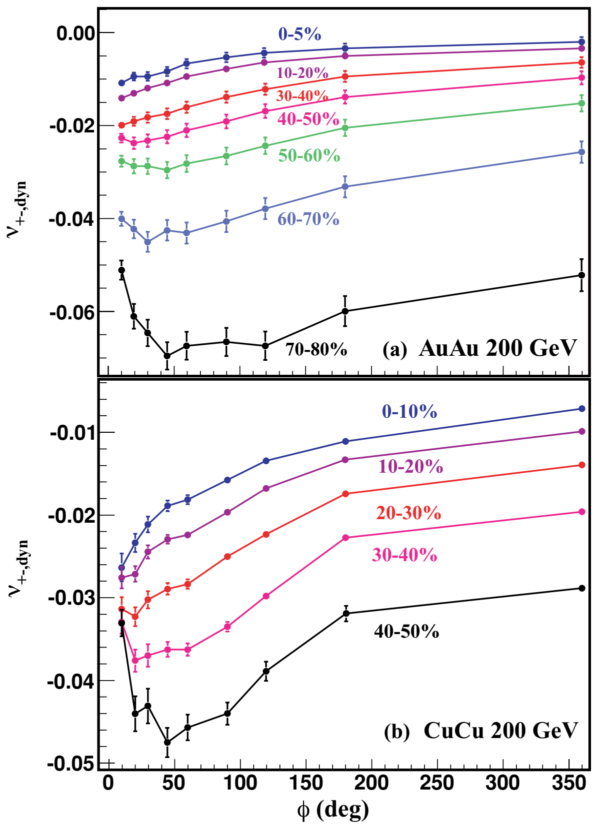

FIG. 5. (Color online) Dynamical fluctuations $\nu_{+-,\mathrm{dyn}}$ as a function of the integrated azimuthal range ϕ for selected collision centralities for (a) Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and (b) Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV.

wedge. The errors shown in Fig. 5 are the statistical errors of the averaged values for each wedge size. We also verified that for small wedge angles (e.g., 90° and smaller), the variances of the measured values, for wedges of a given size, have a magnitude similar to the errors of the averages. Data are shown for seven collision centrality bins in Au + Au collisions in Fig. 5(a) and for five centrality bins in Cu + Cu collisions in Fig. 5(b). Note that the absolute value of the correlation decreases from the most peripheral to the central collisions as a result of progressive dilution with increasing number of participants. The variation of the shape of the correlation function with the size of the azimuthal acceptance is of greater interest. One finds the correlation functions measured in the most central collisions decrease monotonically in magnitude with increasing azimuthal wedge size, whereas they exhibit a more complicated behavior for most peripheral collisions. One expects $\nu_{+-,\mathrm{dyn}}$ to be rather small for very small acceptance (azimuthal wedge), i.e., when the size of the acceptance is smaller than the typical correlation length. This explains why $|\nu_{+-,\mathrm{dyn}}|$ decreases sharply for small angles in peripheral collisions. It is remarkable, however, to note that this behavior is not observed in most central collisions with the angular ranges considered, thereby indicating a change in the particle correlation length qualitatively consistent with the reduction of the balance function in central collisions already reported by STAR [51].

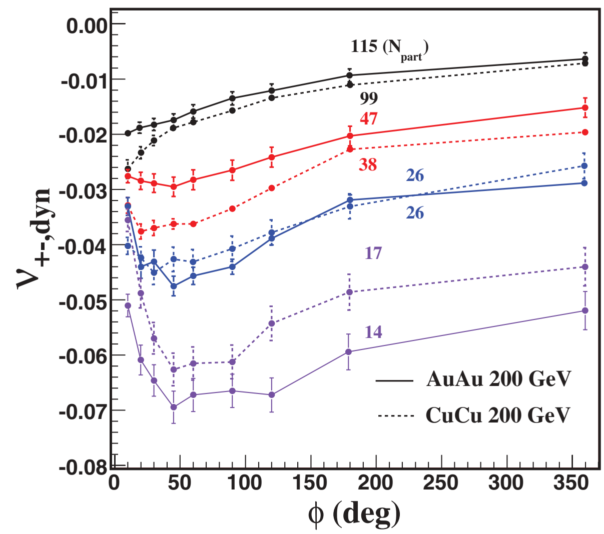

FIG. 6. (Color online) Dynamical fluctuations $\nu_{+-,\mathrm{dyn}}$ as a function of the integrated azimuthal range ϕ for similar number of participating nucleons for Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV.

Figure 6 shows a comparison of Au + Au and Cu + Cu collisions at similar number of participating nucleons. The magnitude of $\nu_{+-,\mathrm{dyn}}$ with respect to the azimuthal angle ϕ is similar for similar number of participating nucleons in both systems with the best agreement for collisions with more than 20 participants. The agreement for the most peripheral collisions studied is weaker, but we speculate that vertex inefficiencies and fluctuations in the number of participants should account for this weaker agreement. We also observe a change in shape with centrality. Both systems show similar monotonic dependence on the angular wedge width ϕ for central collisions. In peripheral collisions, however, the absolute value of $\nu_{+-,\mathrm{dyn}}$ reaches a maximum for a nonzero azimuthal wedge and decreases in magnitude for the smallest values of ϕ. The error bars shown in Fig. 6 are statistical only.

IV. SYSTEMATIC UNCERTAINTIES STUDIES

While $\nu_{+-,\mathrm{dyn}}$ is a robust observable and shown to exhibit essentially no dependence on efficiencies, it may nonetheless be subject to limited systematic effects associated with the measurement process. We investigated dependencies on the longitudinal position of interaction vertex (z vertex), the effect of resonance feed downs, event pile-up, track reconstruction, and p_T resolution.

The dependence of $\nu_{+-,\mathrm{dyn}}$ on the longitudinal position of the interaction vertex might arise because of the restricted acceptance of the TPC on which these analyses are based. We thus measured $\nu_{+-,\mathrm{dyn}}$ by binning events according to the z vertex in steps of 5 cm for positions varying in ranges $5 < |z| < 30$ cm and found deviations in $\nu_{+-,\mathrm{dyn}}$ to be 1% or less.

The $\nu_{+-,\mathrm{dyn}}$ measurement presented in this paper is meant to be representative of particles produced by Au + Au, Cu + Cu, or $p + p$ collisions. By design, one thus seeks to eliminate effects from secondary decays (e.g., $\Lambda \rightarrow p + \pi^-$)

or secondary particle production within the detector. This is accomplished by limiting the analysis to tracks that appear to originate from the collision vertex. Indeed, a cut of track DCA to the collision vertex with a value of 3 cm is used to select primary particles and reduce those produced by decays and secondary interactions. The large value of DCA used in this analysis is due to finite DCA resolution and is also intended to maintain large track detection efficiency, which is needed especially for the $\nu_{+-,\text{dyn}}$ analysis with respect to the longitudinal and azimuthal acceptance. However, with a large value of the DCA cut, one ends up counting particles produced by weak decays (e.g., Λ or K_s^0) as primary particles. In particular, with kaons (K_s^0) representing a small fraction of all neutral particles produced, one expects pions from the decay of these particles to increase the accepted charged particle multiplicity but with only a minor impact on the variance of the measured net charge. This implies that $\nu_{+-,\text{dyn}}$ should be subject to a systematic decrease in magnitude when accepting weak-decay feeddown. We thus studied $\nu_{+-,\text{dyn}}$ for smaller DCA cuts of 2 cm and found that $|\nu_{+-,\text{dyn}}|$ decreases by roughly 1% at all collision centralities. K_s^0 and Λ have a decay length in excess of 2.7 cm. Given the rather limited resolution of the measurement, the DCA of the decay products is spread to values over a range extending more than 3 cm and, thereby, forms a modest background to the primary particles. Assuming the contributions of K_s^0 and Λ are roughly uniform within the 3 cm DCA cut considered, we expect that a 2 cm DCA cut reduces the background by approximately 30%. We observe this change of cut leads to a 1% reduction in the magnitude of $\nu_{+-,\text{dyn}}$. We thus conclude that K_s^0 and Λ contamination amounts to a contribution of a few percent only.

Another important source of secondary tracks not completely eliminated by the DCA cut are electrons/positrons. While a finite electron primary yield is expected from decays of D-mesons and B-mesons, from Dalitz decays of π^0 and η, the bulk of electrons/positrons observed in the TPC are from secondary interactions leading to pair production and from Compton photoelectron production. Elimination of electrons/positrons is, in principle, partly achievable based on cuts on track dE/dx. However, because electrons and pions of low momenta experience similar energy loss in the TPC gas, a cut on the track dE/dx also eliminates a large amount of pions, thereby effectively creating a "hole" in the pion acceptance (with respect to their momentum). We thus carried out the analysis reported in this paper by including the electrons/positrons. Again in this case, since electrons and positrons are typically created in pairs, this may lead to an increase in the integrated charged particle multiplicity with little impact on the net charge variance. One thus expects inclusion of the electrons to produce a systematic shift in the magnitude of $\nu_{+-,\text{dyn}}$. To verify this, we carried out a measurement of $\nu_{+-,\text{dyn}}$ when electrons (and consequently also pions) are eliminated on the basis of the dE/dx cut. The dE/dx cut is accomplished using the truncated mean of the measured dE/dx samples along the track and the track momentum. Tracks were excluded whenever the measured dE/dx fell within two standard deviations of the mean value expected for electrons of a given momentum. We found that when electrons are eliminated, $|\nu_{+-,\text{dyn}}|$ increases by as much as 3.5% in magnitude. This shift, however, may not be entirely due to the suppression of electrons. Indeed, by cutting electrons, one also reduces pion acceptance in transverse momentum. We reported in Sec. III C that $\nu_{+-,\text{dyn}}$ exhibits a modest dependence on the size of integrated longitudinal and azimuthal acceptances. However, a similar (but weaker) dependence on the transverse momentum is expected. It is thus plausible that the shift by 3.5% may in part result from a reduction of pion acceptance. Electron contamination is thus considered a source of systematic uncertainty of the order of 3.5% in our measurement of $\nu_{+-,\text{dyn}}$.

Au + Au and Cu + Cu data acquired during runs IV and V were subject to pile-up effects associated with large machine luminosity obtained during those years. The pile-up may result in two collisions being mistaken as one and treated as such, thereby leading to artificially large multiplicities and increased variances. Therefore, to reject pile-up events, dip angle cuts were introduced in the present analysis. The dip angle is defined as the angle between the particle momentum and the drift direction, $\theta = \cos^{-1}(p_z/p)$. The dip angle cut is based on the average dip angle distribution of all tracks in a given event. We found that the dip angle is correlated with the vertex position and features a width distribution which is Gaussian at low luminosities. We thus reject pile-up events that are beyond two standard deviations of the mean of the distribution for a particular centrality and vertex position. We found that $\nu_{+-,\text{dyn}}$ changes by less than 1% when the dip angle cut is used.

We also checked the effect of efficiency variation within the acceptance of interest. The efficiency is known in particular to progressively reduce from a maximum value for $p_T >$ 200 MeV/c to zero for $p_T <$ 100 MeV/c. We determined an upper bound of the effect of p_T dependence by measuring $\nu_{+-,\text{dyn}}$ with p_T thresholds of 150 and 200 MeV/c. We found changes of $\nu_{+-,\text{dyn}}$ are typically negligible within the statistical accuracy of our measurement and amount to at the most 1.5%.

Total systematic uncertainty contribution increases from 8% to 9% from central to peripheral collisions in Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. Similarly, systematic uncertainties amount to 8% in peripheral collisions and 7% in central collisions in Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV. The systematic uncertainties on $\nu_{+-,\text{dyn}}$ from different sources mentioned above are added linearly.

V. SUMMARY AND CONCLUSIONS

We have presented measurements of dynamical net charge fluctuations in Au + Au collisions at $\sqrt{s_{NN}} =$ 19.6, 62.4, 130, 200 GeV, Cu + Cu collisions at $\sqrt{s_{NN}} = 62$ and 200 GeV, and $p + p$ collisions at $\sqrt{s} = 200$ GeV, using the measure $\nu_{+-,\text{dyn}}$. We observed that the dynamical net charge fluctuations are nonvanishing at all energies and exhibit a modest dependence on beam energy in the range $19.6 \leqslant \sqrt{s_{NN}} \leqslant 200$ GeV for Au + Au as well as Cu + Cu collisions. Dynamical fluctuations measured in this work are in quantitative agreement with measurements by the CERES Collaboration at $\sqrt{s_{NN}} = 17.2$ GeV and PHENIX Collaboration at $\sqrt{s_{NN}} = 130$ GeV. However, measurements by CERES at lower beam energy ($\leqslant$17.2 GeV) exhibit much smaller dynamical net charge fluctuations perhaps owing to a transition from baryon to meson dominance in the SPS energy regime. We also found the dynamical net charge fluctuations violate the trivial $1/N_{\rm ch}$ scaling expected for nuclear collisions consisting of independent nucleon-nucleon interactions. However, one finds that $\nu_{+-,\rm dyn}$ scaled by the number of participants exhibits little dependence on collision centrality but shows modest dependence on collision systems. Measured values of $\nu_{+-,\rm dyn}$ are inconsistent for all systems and energies with the predictions of the QGP hadronization model of Koch *et al.* [1–3]. Given the reported observations of a strongly interacting medium in $A + A$ collisions at RHIC, this suggests that the assumptions of the hadronization by Koch *et al.* are invalid, or that some final state interaction process washes out the predicted signal. Scaled dynamical net charge fluctuations $|\nu_{+-,\rm dyn}\, dN_{\rm ch}/d\eta|$ grow by up to 40% from peripheral to central collisions. We speculated that the centrality dependence arises in part because of the large radial collective flow produced in Au + Au collisions and proceeded to study fluctuations as a function of azimuthal angle and pseudorapidity. Our analysis showed that dynamical fluctuations exhibit a strong dependence on rapidity and azimuthal angular ranges which could be attributed in part to radial flow effects.

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