Multiplicity and mean transverse momentum fluctuations in Au + Au collisions at RHIC.

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Abstract. Strong modification of event-by-event fluctuations in global observables was proposed by several authors as an indicator of the phase transition in system evolution. We report the results of the analysis of STAR TPC data on the charged multiplicity and mean transverse momentum fluctuations in Au+Au collisions at $\sqrt{s_{NN}}$=130 GeV. We discuss the centrality dependence of the observed fluctuations and compare the results with available data from lower collision energies and ISR data.

INTRODUCTION

The question of the hadronization of the system created in ultrarelativistic heavy ion collisions is one of the most interesting in this field. Does the system evolution include the phase transition? Event-by-event fluctuations of the mean transverse momentum and/or multiplicity, are considered to be one of the important tools to identify such a phase transition. The fluctuations depend on the nature of the phase transition. A first order phase transition may lead to large fluctuations in energy density due to formation of QGP droplets[1, 2]. Second order phase transitions may lead to divergence in the specific heat; it would also increase the fluctuations in energy density due to long range correlations in the system [3, 4]. One could observe them as fluctuations in mean transverse momentum if matter freezes out at the critical temperature T_c [5, 6]. The system freeze-out near the QCD tri-critical and critical points would also lead to change in the fluctuations pattern [3, 4, 7]. There exist also other sources of the abnormal dynamical fluctuations. The formation of the disoriented chiral condensate [8] should lead to large fluctuations in the ratio of neutral to charged pion yields at low p_t, and consequently to fluctuations in $\langle p_t \rangle$ of charged particles. Jets may give rise to event-by-event fluctuations in the high p_t region.

For the multiplicity fluctuations, predictions range from enhanced multiplicity fluctuations connected to the production of QGP droplets and nucleation processes in a first order phase transition, to a strong suppression of fluctuations as a consequence of rapid freeze-out just after the phase transition. In this case, final state values of conserved quantities, such as net electric charge, baryon number, and strangeness would not be strongly modified from their value in the QGP stage. The fluctuation of these quantities could be reduced by a factor $2-4$ if a QGP is produced [9, 10]. The production and size of QGP droplets may critically depend on the collision impact parameter, leading to centrality dependence of the fluctuations to be an important observable. If the fluctuations are due to the particle production via any kind of clusters (e.g., resonances, strings (mini)jets, independent NN-collisions, etc.) and the relative production of such clusters do not change with centrality, the correlation strength should be inversely proportional to the particle multiplicity. New physics could indicate itself as a deviation from such a dependence.

Here, we report on our measurement of charged particle multiplicity and mean p_t fluctuations as a function of collision centrality in Au + Au collisions at an energy of $\sqrt{s_{NN}} = 130$ GeV. Specifically, in a case of multiplicity fluctuations we discuss fluctuations in the difference of the relative number of produced positive and negative charged particles measured in a fixed rapidity range:

$$\nu_{ab} = \langle \left(\frac{N_a}{\langle N_a \rangle} - \frac{N_b}{\langle N_b \rangle} \right)^2 \rangle, \tag{1}$$

where N_a and N_b are the corresponding multiplicities. One could consider fluctuations in the production of charged particles, N_+ and N_-, as well as specific cases of proton and anti-proton, N_p and $N_{\overline{p}}$, and positive and negative kaons,

N_{K+} and N_{K-}, fluctuations. The former amounts to a measurement of net electrical charge fluctuations, whereas the latter is related to net baryon number and net strangeness fluctuations. The quantity ν_{ab} used in our analysis can be related to the fluctuations in multiplicity ratios [12, 11], but the have advantage of not being limited to large particle multiplicities.

Statistical and Dynamical fluctuations

The fluctuations of any observable measured on an event-by-event basis consists of two parts: statistical fluctuations, the uncertainty in the measurement of a given quantity due to finite event multiplicity, and dynamical fluctuations due to correlated particle production, the subject of interest. The statistical fluctuations are the ones one would observe in case of independent particle production provided the single particle inclusive quantities remain the same as in a real events.

Multiplicity fluctuations. A difficulty inherent in the interpretation of multiplicity fluctuations is the elimination of effects associated with uncertainties in the collision centrality, often referred to as volume fluctuations. They, in particular, induce a positive correlation in particle production which does not depend on the intrinsic dynamical properties of the colliding system. Fluctuations in the difference of relative multiplicities, ν_{ab}, defined in Eq. 1, are however free from this problem. This analysis is thus restricted to the study of such relative multiplicities.

The magnitude of the variance, ν_{ab}, is determined by both statistical and dynamical fluctuations. Taking into account that in the case of independent particle production the multiplicity fluctuations follow the Poisson distribution, the dynamical fluctuations can be evaluated as

$$\nu_{ab,dyn} = \nu_{ab} - \nu_{ab,stat}, \quad \nu_{ab,stat} = \frac{1}{\langle N_a \rangle} + \frac{1}{\langle N_b \rangle}. \tag{2}$$

The value of $\nu_{ab,dyn}$ is determined by intrinsic correlations between produced particles averaged over the pseudo-rapidity and transverse momentum range under study. It is, to first order, independent of the detector acceptance and particle detection efficiency as can be seen from its relation to the inclusive two and single particle densities:

$$\nu_{ab,dyn} = R_{aa} + R_{bb} - 2R_{ab}, \tag{3}$$

where R_{ab} is a correlation function similar to that used in multi-particle production analysis [13, 14, 15] and defined as

$$R_{ab} = \frac{\int_{\Delta Y} \rho_{2,ab}(\eta_a, \eta_b) d\eta_a d\eta_b}{\int_{\Delta Y} \rho_{1,a}(\eta_a) d\eta_a \int_{\Delta Y} \rho_{1,b}(\eta_b) d\eta_b} - 1, \tag{4}$$

where $\rho_1(\eta) = dn/d\eta$, and $\rho_2(\eta_a, \eta_b) = d^2n/d\eta_a d\eta_b$ are single and two particle (pseudo)rapidity density respectively.

Mean transverse momentum fluctuations. We use the following notation for the mean transverse momentum in each event and average over all events in a given event sample (centrality bin):

$$\langle p_t \rangle = \frac{1}{M} \sum_{i=1}^{M} p_{t_i}, \quad \langle \langle p_t \rangle \rangle = \frac{1}{N_{evt}} \sum_{j=1}^{N_{evt}} \langle p_t \rangle_j. \tag{5}$$

The fluctuations in $\langle p_t \rangle$ would be

$$\sigma^2_{\langle p_t \rangle} = \langle \langle p_t \rangle^2 \rangle - \langle \langle p_t \rangle \rangle^2 = \frac{1}{M^2} \langle \langle \sum_i p_{t,i}^2 + \sum_{i \neq j} p_{t,i} p_{t,j} \rangle \rangle - \langle \langle p_t \rangle \rangle^2 \tag{6}$$

$$= \sigma^2_{\langle p_t \rangle, stat} + \frac{M-1}{M} \sigma^2_{\langle p_t \rangle, dynam}, \quad \text{with} \quad \sigma^2_{\langle p_t \rangle, stat} = \frac{\langle \langle p_t^2 \rangle \rangle - \langle \langle p_t \rangle \rangle^2}{M} = \frac{\sigma^2_{p_t, inclusive}}{M}. \tag{7}$$

where M is the multiplicity. In Eq. 7 we have introduced the notation for the non-statistical (dynamical) fluctuations in $\langle p_t \rangle$ as:

$$\sigma^2_{\langle p_t \rangle, dynam} \equiv \langle \langle p_{t,i} p_{t,j} \rangle \rangle_{i \neq j} - \langle \langle p_t \rangle \rangle^2, \tag{8}$$

which is zero in the case of no correlation between particle transverse momenta. As above, in this equation the double angle brackets mean the average over particle pairs in some (pseudo)rapidity and transverse momentum window, and the average over all events with a given multiplicity.
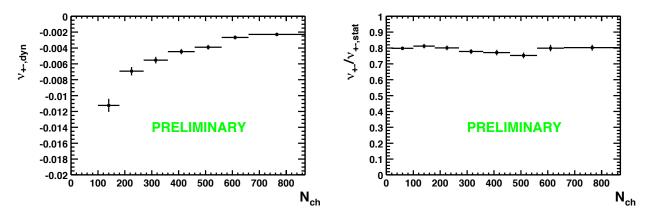
FIGURE 1. (left) $\nu_{+-,dyn}$ as a function of centrality (event raw multiplicity), and (right) $\nu_{+-}/\nu_{+-,stat} \approx 1 + (\langle N_+ \rangle + \langle N_- \rangle)\nu_{+-,dyn}/4$.

RESULTS

STAR detector and data selection. The STAR detector consists of many detector subsystems in a large solenoidal magnet with the Time Projection Chamber (TPC) as the main tracking device. Details about the STAR TPC can be found in reference[17]. In the year 2000, the TPC was operated in a 0.25 T magnetic field allowing tracking of particles with p_t greater than 75 MeV/c. The experimental setup includes also the scintillator trigger barrel (CTB) surrounding the TPC and two Zero Degree Calorimeters (ZDCs) located at 18 m from the center of the TPC. The ZDCs measure mainly fragmentation neutrons and are used in coincidence as experimental trigger for minimum bias events.

We determine the centrality of the collision by the total charged reconstructed track multiplicity, N_{ch}, in the pseudorapidity region $|\eta| < 0.75$. Eight centrality bins used in this analysis are the same as used in [19] and correspond to the fraction of the total geometrical cross section of top 6%, 11%, 18%, 26%, 34%, 45%, 58%, and 85%, respectively.

A total of about 190 thousand minimum bias events with a primary vertex position within 75 cm of the center of the TPC have been used in this analysis. The tracks are required to pass within 3 cm of the primary vertex and the ratio of the number of points on a track to the maximum possible number of points is required to be greater than 0.5 in order to avoid double counting of tracks due to track splitting. In this analysis we use only tracks within the pseudo-rapidity range $-0.75 < \eta < 0.75$ and transverse momentum $0.150 < p_t < 2.0$ GeV/c, where the track reconstruction efficiency is estimated to be constant within $\pm 10\%$.

Multiplicity fluctuations. Fig.1 shows the dynamical fluctuations, $\nu_{+-,dyn}$, in the pseudorapidity region $-0.5 < \eta < 0.5$, as a function of the total multiplicity N_{ch}. The dynamical fluctuations are finite and negative: a clear indication of the correlation in the production of the positive and negative particles. We verified that, within statistical errors, the same value is obtained when the pseudorapidity regions used to count positive an negative tracks were separated by a $\Delta\eta = 0.125$ gap, which should eliminate problems related to track splitting and resolution of two close tracks. We observe less than 10% decrease in the strength of the correlation varying pseudo-rapidity range from 0.125 to 0.75.

The absolute strength of the dynamical fluctuations decreases monotonically with increasing collision centrality. In order to check the deviation from the inverse proportionality to multiplicity, in Fig.1b we present the ratio of the observed fluctuations to the statistical fluctuations[1]. This ratio is related to the quantities ω_Q and D used in other works [9, 10, 27] as $\nu_{ab}/\nu_{ab,stat} \approx \omega_Q = \delta Q^2/N_{ch} = 0.25D$. The relationship is strictly exact if $\langle N_+ \rangle = \langle N_- \rangle$. The ratio has a value of about 0.8 nearly independent of the collision centrality in qualitative agreement with a value of 0.75 expected based on a thermalized resonance gas as calculated in [11] for particles produced in a rapidity interval $\Delta y = 1$. The measurement however deviates drastically from calculations based on a rapid QGP freeze out [10, 9], which predict values of ≈ 0.2–0.4.

We consider these results in the light of correlation functions measured in $p\bar{p}$ collisions at CERN [18, 20, 13]

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[1] Note, that this ratio depends on the size of the acceptance used for the measurement.

with the use of Eq.3. We account for the unavailability of measurements at the same energy by interpolating the data obtained at lower and higher collision energies (parameterization from [21]). We also note that the correlation function for opposite charge particles, R_{+-}, is found to be approximately twice as strong as the same sign particles correlations, $R_{++} \approx R_{--}$ [13, 14], and independent of the collision energy. Using the single charge particle pseudorapidity density $\rho_1(\eta = 0) \approx 2.05$ and $C_2(0,0) = \rho_2(\eta_1 = 0, \eta_2 = 0) - \rho_1(\eta_1 = 0)\rho_1(\eta_2 = 0) \approx 2.8$ one finds $R_{cc} \approx 0.66$. Furthermore, assuming equal multiplicities of positively and negatively charged particles, one finds $R_{cc} \approx (R_{++} + R_{--} + 2R_{+-})/4 \approx 1.5R_{++}$, which we use to estimate the correlation measured in this work as $R_{++} + R_{--} - 2R_{+-} \approx -2R_{++} \approx 4R_{cc}/3 \approx 0.88$. Under assumption that the correlations are due to production in a finite number of sources (clusters), they should be inversely proportional to the particle density. In central Au+Au collisions, the charged particle density is about 550 compared to approximately 2.06 in $p\bar{p}$ collision. Such a dilution would give for the correlation function a value of $0.88 \cdot 2.06/550 \approx 0.003$, a number which is about 30% larger than we observe (see Fig.1a).

Mean p_t fluctuations. The results for the mean transverse momentum fluctuation in the region $-0.75 < \eta < 0.75$ are presented in Fig. 2. Selecting different pairs for the averaging in Eq. 8 one can suppress or enhance contribution to $\langle p_t \rangle$
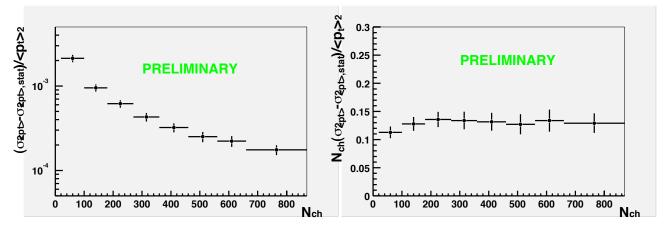

FIGURE 2. (left) $\sigma^2_{\langle p_t \rangle, dynam} \langle\langle p_t \rangle\rangle^2$ as a function of centrality (event raw multiplicity), and (right) the same scaled with multiplicity.

fluctuations of different origin. We have also correlated: (1) particles in pseudo-rapidity region $-0.75 < \eta < -0.05$ with particles in $0.05 < \eta < 0.75$. The 'gap' between the two regions eliminates effects such as Bose-Einstein correlations(HBT) or Coulomb final state interactions. (2) Positive particles with negative particles, which is expected to enhance the contribution from resonances. No significant difference has been observed. The somewhat smaller value (less than 10%) in the case of the correlation of particle separated by the gap in pseudorapidity could be explained by larger average distance in the pseudorapidity space between the two particles in a pair. The relative fluctuation in mean transverse momentum was found to be $\sigma_{dynam}/\langle\langle p_t \rangle\rangle \approx 1.2 \pm 0.2\%$. The (relative) systematic error in our measurements of $\sigma^2_{\langle p_t \rangle, dynam}$ is about 5%. It has been estimated by varying track selection cuts, primary vertex position within the TPC, and comparing the Monte-Carlo results before and after processing through the detector simulation.

Event-by-event dynamical fluctuations have been also analyzed by several experiments using the so called Φ_{p_t} [22] measure (the approximate relation to $\sigma^2_{\langle p_t \rangle, dynam}$ is taken from [16]):

$$\Phi_{p_t} \equiv \sqrt{\langle((\langle p_t \rangle - M\overline{p_t})^2)\rangle / \langle M \rangle} - \sigma_{p_t, inclusive} \approx \frac{\sigma^2_{\langle p_t \rangle, dynam}\langle M \rangle}{2\sigma_{p_t, inclusive}}. \tag{9}$$

and close to it the difference factor $\Delta\sigma_{p_t}$ [25]:

$$\Delta\sigma_{p_t} \equiv (\sqrt{\langle M \rangle}\sigma_{p_t, inclusive} - \sigma_{p_t, inclusive}) \approx \Phi_{p_t}. \tag{10}$$

For the 6% most central collisions STAR measures [25] $\Delta\sigma_{p_t} \approx 35\ MeV$, which is consistent with results reported here for $\sigma_{\langle p_t \rangle, dynam}$ (one can check it with the help of an approximate expression given by Eq. 9 and using the other necessary parameters presented in [25]). In Pb+Pb and Pb+Au collisions at CERN SPS ($\sqrt{s_{NN}} = 17$ GeV) Φ_{p_t} have been measured by the NA49 experiment [23] and NA45/CERES collaboration [26]. The NA49 collaboration reported [23] $\Phi_{p_t} = 0.6 \pm 1$ MeV/c for the rapidity region $4.0 < y < 5.5$ and 5% most central collisions. The observed fluctuations

are very small, but it would be confusing to compare these numbers with STAR measurement, because NA49 results have been obtained in the forward rapidity region, while STAR measurements are done at midrapidity. The CERES collaboration has measured the fluctuations in the central rapidity region. They reported $\Phi_{p_t} = 7.8 \pm 0.9$ MeV/c in central Pb+Au collisions [26]. As seen from Eq. 9, Φ_{p_t} is directly proportional to the number of reconstructed tracks used for its calculation (subject to acceptance cuts and tracking efficiency) which complicates the comparison of the results from different experiments. For a rough comparison one can take into account that CERES multiplicity is close to 130 and their $\langle\langle p_t \rangle\rangle \approx 420$ GeV/c and $\sigma_{pt,\,inclusive} \approx 0.270$ GeV/c. Then $\Phi_{p_t} \approx 8$ MeV corresponds to $\sigma_{\langle p_t \rangle,dynam}/\langle\langle p_t \rangle\rangle \approx 1.4\%$.

The dynamical part in mean transverse momentum fluctuations has been measured at ISR [24] in $p\bar{p}$ collisions. It was done by analyzing the multiplicity dependence of $\sigma_{\langle p_t \rangle}$ and under assumption that in $p\bar{p}$ collisions the dynamical part in $\langle p_t \rangle$ fluctuation does not depend on multiplicity. It was observed that $\sigma_{\langle p_t \rangle,dynam}/\langle\langle p_t \rangle\rangle \approx 12\%$. Rescaling of this quantity with (square root of) the ratio of multiplicity densities in $p\bar{p}$ and $Au + Au$ collisions would yield the fluctuations in $Au + Au$ of $\sigma_{\langle p_t \rangle,dynam}/\langle\langle p_t \rangle\rangle \approx 0.8\%$, about 50% less than observed in our experiment.

To understand the role of (mini)jet production in $\langle p_t \rangle$ fluctuations we have performed an analysis of central HIJING events with hard processes switched "on" or "off" and with the same cuts as real experimental data. The jets increase the fluctuations for about 10% from $\sigma_{\langle p_t \rangle,dynam}/\langle\langle p_t \rangle\rangle \approx 1.0\%$ to about 1.1%. Note that both numbers are very close to the experimentally observed value. Contrary to HIJING, the RQMD event generator includes secondary particle rescatterings, but yields approximately (within 20%, limited by our statistics of the RQMD events) the same values as HIJING.

In **summary**, we have reported the first measurements of the multiplicity and mean transverse momentum fluctuations in Au+Au collisions at RHIC. While a clear correlation in particle production has been measured, no qualitative difference from the lower energy AA collision experiments as well as pp collisions at similar energies has been observed. The centrality dependence of the observed correlations is consistent with being inversely proportional to total event multiplicity, the dependence expected in particle production via clusters.

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