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We present results for two-particle transverse momentum correlations, $\langle \Delta p_{t,i} \Delta p_{t,j} \rangle$, as a function of event centrality for Au+Au collisions at $\sqrt{s_{NN}}$ = 20, 62, 130, and 200 GeV at the Relativistic Heavy Ion Collider. We observe correlations decreasing with centrality that are similar at all four incident energies. The correlations multiplied by the multiplicity density increase with incident energy and the centrality dependence may show evidence of processes such as thermalization, jet production, or the saturation of transverse flow. The square root of the correlations divided by the event-wise average transverse momentum per event shows little or no beam energy dependence and generally agrees with previous measurements at the Super Proton Synchrotron.

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The study of event-by-event fluctuations in global quantities, which are intimately related to correlations in particle production, may provide evidence for the production of the quark gluon plasma (QGP) in relativistic heavy ion collisions [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Various theoretical work predicts that the production of a QGP phase in relativistic heavy ion collisions could produce significant dynamic event-by-event fluctuations in apparent temperature, mean transverse momentum, multiplicity, and conserved quantities such as net charge. Several recent experimental studies at the SPS [16, 17, 18] and at RHIC [19, 20, 21, 22, 23, 24] have focused on the study of fluctuations and correlations in relativistic heavy ion collisions. One possible signal of the QGP would be a non-monotonic change in p_t correlations as function of centrality and/or as the incident energy is raised [8].

Here we report an experimental study of the incident energy dependence of p_t correlations using Au+Au collisions ranging in center of mass energy from the highest SPS energy to the highest RHIC energy using the STAR detector at RHIC.

Fluctuations involve a purely statistical component arising from the stochastic nature of particle production and detection processes, as well as a dynamic component determined by correlations arising in various particle production processes. In this paper we first unambiguously demonstrate the existence of a finite dynamical component at all four incident energies by comparing the distribution of measured event-wise average transverse momentum per event, $\langle p_t \rangle$, with the same quantity from mixed events. We then analyze these dynamical fluctuations using the two particle transverse momentum correlations defined as covariance

$$\langle \Delta p_{t,i} \Delta p_{t,j} \rangle = \frac{1}{N_{\text{event}}} \sum_{k=1}^{N_{\text{event}}} \frac{C_k}{N_k(N_k-1)} \tag{1}$$

where

$$C_k = \sum_{i=1}^{N_k} \sum_{j=1, i \neq j}^{N_k} \left(p_{t,i} - \langle\langle p_t \rangle\rangle\right)\left(p_{t,j} - \langle\langle p_t \rangle\rangle\right) \tag{2}$$

and N_{event} is the number of events, $p_{t,i}$ is the transverse momentum of the i^{th} track in each event, N_k is the number of tracks in the k^{th} event. The overall event average transverse momentum $\langle\langle p_t \rangle\rangle$ is given by

$$\langle\langle p_t \rangle\rangle = \left(\sum_{k=1}^{N_{\text{event}}} \langle p_t \rangle_k \right) / N_{\text{event}} \tag{3}$$

where $\langle p_t \rangle_k$ is the average transverse momentum per event given by

$$\langle p_t \rangle_k = \left(\sum_{i=1}^{N_k} p_{t,i} \right) / N_k. \tag{4}$$

$\langle \Delta p_{t,i} \Delta p_{t,j} \rangle$ is independent, to first order, of detection efficiencies because both the numerator C_k and the denominator $N_k(N_k-1)$ are proportional to the the square of the particle detection efficiency. Therefore the efficiency cancels. By construction $\langle \Delta p_{t,i} \Delta p_{t,j} \rangle$ is zero within statistics for properly mixed events because all correlations are removed. Note that we use mixed events only in Figure 1.

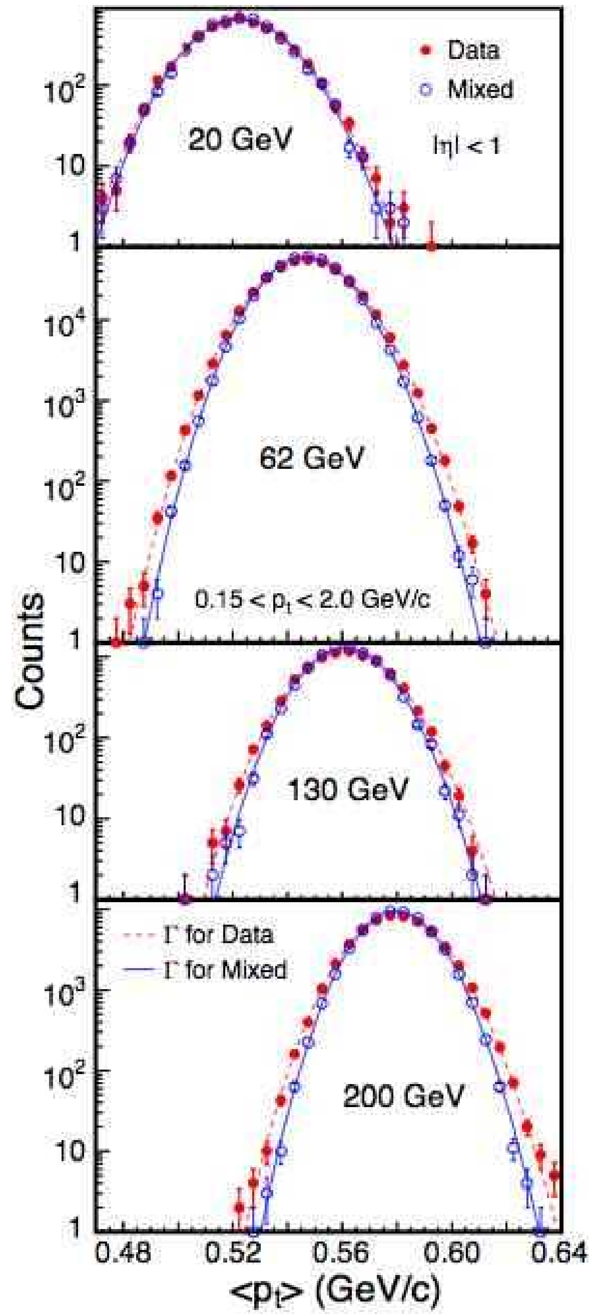

FIG. 1: (Color online) Histograms of the average transverse momentum per event for Au+Au at $\sqrt{s_{NN}}$ = 20, 62, 130, and 200 GeV for the 5% most central collisions at each energy. Both data and mixed events are shown for each incident energy. The lines represent gamma distributions.

The data used in this analysis were measured using the Solenoidal Tracker at RHIC (STAR) detector to study Au+Au collisions at $\sqrt{s_{NN}}$ = 20, 62, 130, and 200 GeV [25]. The main detector was the Time Projection Chamber (TPC) located in a solenoidal magnetic field. The magnetic field was 0.25 T for the 20 and 130 GeV data and 0.5 T for the 62 and 200 GeV data. Tracks from the TPC with 0.15 GeV/c $\leq p_t \leq$ 2.0 GeV/c with $|\eta| < 1.0$ were used in the analysis. All tracks were required to have originated within 1 cm of the measured event vertex. Events were selected according to their distance of the event vertex from the center of STAR. Events were accepted within 1 cm of the center of STAR in the plane perpendicular to the beam direction. For the 20 and 130 GeV data sets, events were accepted with vertices within 75 cm of the center of STAR in the beam direction, while for the 62 and 200 GeV data sets, events were accepted within 25 cm of the center.

Data shown for 62, 130 and 200 GeV are from minimum bias triggers. Minimum bias triggers were defined by the coincidence of two Zero Degree Calorimeters (ZDCs) [26] located ± 18 m from the center of the interaction region. For 20 GeV a combination of minimum bias and central triggers was used. Centrality bins were determined using the multiplicity of all charged particles measured in the TPC with $|\eta| < 0.5$. The centrality bins were calculated as fractions of this multiplicity distribution starting with the highest multiplicities. The ranges used were 0-5% (most central), 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, and 70-80% (most peripheral). Each centrality was associated with a number of participating nucleons, N_{part}, using a Glauber Monte Carlo calculation [27].

We treated the variation of $\langle\langle p_t\rangle\rangle$ within a given centrality bin using the following procedure. We calculated $\langle\langle p_t\rangle\rangle$ as a function of N_{ch}, the multiplicity used to define the centrality bin. We fitted this dependence and used the fit in Eqs. 1-4 on an event-by-event basis as a function of N_{ch}. This method removes the dependence of the experimental results on the size of the centrality bin and slightly reduces $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ by removing correlations induced by the changing of $\langle\langle p_t\rangle\rangle$ within the experimental centrality bins. The results presented in the paper are obtained using this fitting procedure.

Fig. 1 shows histograms of $\langle p_t\rangle$ for the 5% most central Au+Au collisions at 20, 62, 130, and 200 GeV. Histograms for $\langle p_t\rangle$ are also shown for mixed events. The histograms for the data are wider than the histograms for mixed events indicating that we observe non-statistical fluctuations at all four incident energies. Similar results are obtained for all centralities. The overall normalization reflects the number events taken at each energy. The values of p_t included in these histograms are not corrected for experimental momentum resolution, acceptance or efficiency.

The mixed events at each energy were created by randomly selecting one track from an event chosen from measured events in the same centrality and event vertex bin. Ten centrality bins and either five or ten bins (depending on the available number of events at each energy) in the event vertex position in the beam direction were used to create mixed events with the same multiplicity distribution as the real events. Note that we do not use mixed events for the quantitative analysis based on $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$.

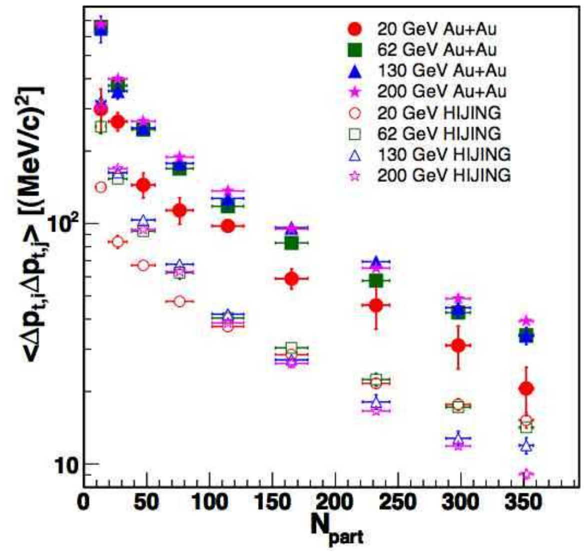

FIG. 2: (Color online) $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ as a function of centrality and incident energy for Au+Au collisions compared with HIJING results.

The lines in Fig. 1 represent gamma distributions for both the data and mixed events. The parameters for the gamma distributions are shown in Table 1. According to Ref. [28], without p_t cuts the parameter α divided by the average multiplicity in the centrality bin, $\langle N\rangle$, should be approximately two and the parameter β multiplied by $\langle N\rangle$ should reflect the temperature parameter of the p_t distributions. We find that $\alpha/\langle N\rangle$ varies from 2.27 to 1.93 and $\beta\langle N\rangle$ varies from 0.230 to 0.299 GeV/c as the energy goes from 20 to 200 GeV.

TABLE I: Parameters for the gamma distributions shown in Fig. 1. The gamma distribution is given by the form $f(x) = \frac{x^{\alpha-1}e^{-x/\beta}}{\Gamma(\alpha)\beta^{\alpha}}$ where $\alpha = \frac{\mu^2}{\sigma^2}$ and $\beta = \frac{\sigma^2}{\mu}$ in GeV/c. μ is the mean in GeV/c and σ is the standard deviation in GeV/c.

Case	α	β	μ	σ
20 GeV Real	1096	4.772 x 10^{-4}	0.5228	0.01579
20 GeV Mixed	1199	4.360 x 10^{-4}	0.5227	0.01510
62 GeV Real	1445	3.786 x 10^{-4}	0.5471	0.01439
62 GeV Mixed	1743	3.139 x 10^{-4}	0.5470	0.01310
130 GeV Real	1556	3.608 x 10^{-4}	0.5614	0.01423
130 GeV Mixed	1917	2.927 x 10^{-4}	0.5612	0.01282
200 GeV Real	1853	3.129 x 10^{-4}	0.5799	0.01347
200 GeV Mixed	2373	2.443 x 10^{-4}	0.5799	0.01190

To characterize the transverse momentum correlations, we use the the quantity $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$, defined in Eq. 1. Fig. 2 shows $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ for Au+Au collisions at $\sqrt{s_{NN}}$ = 20, 62, 130, and 200 GeV as a function of centrality. One observes that $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ decreases with centrality at all four energies as expected due to a progressive

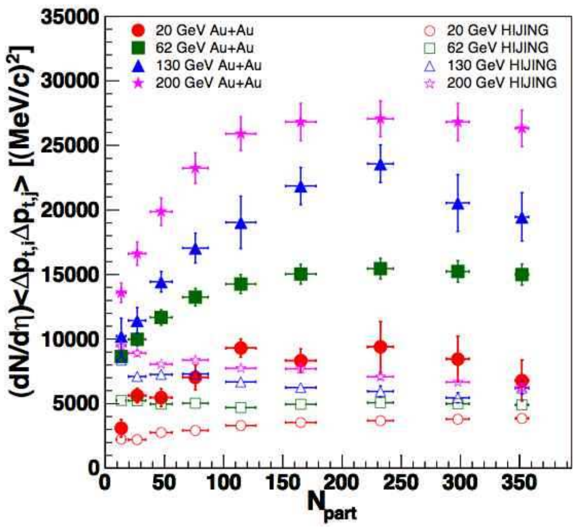

FIG. 3: (Color online) $(dN/d\eta)\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ as a function of centrality and incident energy for Au+Au collisions compared with HIJING results.

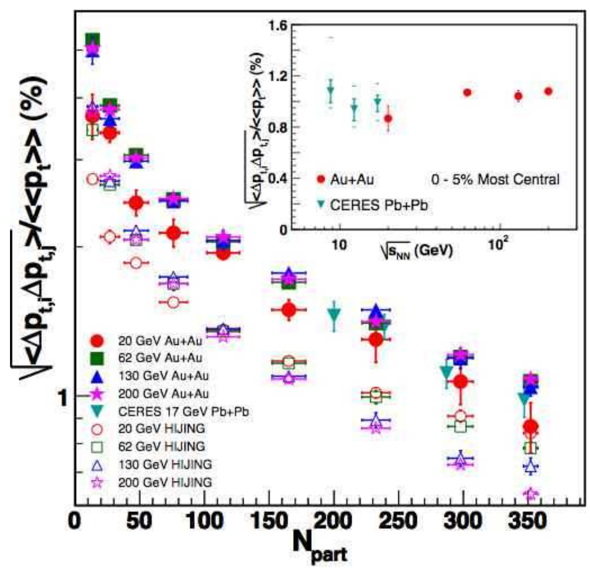

FIG. 4: (Color online) $\sqrt{\langle\Delta p_{t,i}\Delta p_{t,j}\rangle}/\langle\langle p_t\rangle\rangle$ as a function of centrality and incident energy for Au+Au collisions compared with HIJING results for corresponding systems. The inset shows the excitation function for the most central bin.

dilution of the correlations resulting from the increased number of participants if the correlations are dominated by pairs of particles that originate from the same nucleon-nucleon collision. The correlations measured at 62, 130 and 200 GeV are similar while the correlations for 20 GeV are smaller than those observed at the higher energies.

To explore the issue of the relative importance of short range correlations such as Coulomb interactions and Hanbury Brown-Twiss (HBT) effects, we extracted the correlations excluding pairs with invariant relative momentum, q_{inv}, less than 0.1 GeV/c, assuming that all particles were pions. We observed that 10% of the measured correlations at 62, 130, and 200 GeV and 20% of measured correlations at 20 GeV could be attributed to these short range correlations. These estimates agree with those extracted for 17 GeV Pb+Pb [16] using a somewhat different method. We also estimated the contribution of resonances and other charge-ordering effects by studying the reduction in the correlations for same charge (negative) particles compared with correlations for all charged particles. This study indicated that the reduction in $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ is 40% at 20 GeV, 20% at 62 and 130 GeV, and 15% at 200 GeV. We do not correct $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ for short range correlations or resonance contributions.

The errors shown in all figures are statistical unless otherwise noted. We estimate the systematic relative errors for $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ using studies of the effects of p_t-dependent efficiencies (1.2%) and sensitivity to track merging and splitting (1.4%). These values give an overall systematic relative error of 2%. The measured correlations were lowered approximately 3% using the fitting method rather than the binning method. The reported values are sensitive to the p_t cuts for kinematic and physics reasons. Using HIJING [29] we observe a 6% increase in correlations when the lower p_t cut is removed. Raising the upper p_t cut increases the correlations. We used 0.15 GeV/c $\leq p_t \leq$ 2.0 GeV/c for all the results reported in this paper. The upper p_t cut was chosen to be consistent with previous work [19, 24].

Also shown in Fig. 2 are HIJING calculations for Au+Au collisions at $\sqrt{s_{NN}}$ = 20, 62, 130, and 200 GeV [29]. We used HIJING version 1.36 with the default options, which includes jet quenching. The HIJING results were obtained by selecting particles with 0.15 GeV/c $\leq p_t \leq$ 2.0 GeV/c with $|\eta| < 1.0$ without further efficiency corrections. HIJING reproduces correlations in p+p and α+α collisions at Intersecting Storage Ring (ISR) energies [30], p+p collisions at RHIC energies, and p+$\bar{\text{p}}$ collisions at CERN p+$\bar{\text{p}}$ Collider (SppS) energies [31]. We use HIJING to provide a reference incorporating a superposition of nucleon-nucleon interactions. Any differences between HIJING and the experimental results might signal phenomena unique to nucleus-nucleus collisions. The HIJING calculations exhibit little incident energy dependence and decrease with increasing centrality. The values for $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ predicted by HIJING are always smaller than the data.

To address the observed dilution of the correlations with centrality, and to check the hypothesis that the correlations scale as inverse multiplicity, we multiply$\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ by the charged particle pseudorapidity density at a given centrality, $dN/d\eta$. We use fully corrected values for $dN/d\eta$ from published work [32, 33, 34]. The quantity $\frac{dN}{d\eta}\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ then is insensitive to efficiency and is similar to the (efficiency corrected) quantity $\Delta\sigma_{pt}$ [19] that STAR has reported previously.

In Fig. 3 we show the quantity $\frac{dN}{d\eta}\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ for Au+Au collisions at 20, 62, 130, and 200 GeV as a function of centrality. In this figure the errors include the quoted errors in $dN/d\eta$. This quantity increases with incident energy at all centralities. At each energy this measure of the correlations increases quickly as the collisions become more central and then saturates in central collisions. The behavior of this quantity is similar to that of the quantity $\Delta\sigma_{pt}$ previously studied by STAR [19]. This saturation might indicate effects such as the onset of thermalization [15], the onset of jet quenching [14], the saturation of transverse flow [35] in central collisions, or other processes.

In Fig. 3 the results of HIJING calculations for $\frac{dN}{d\eta}\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ are also shown. In contrast to the experimental results, the HIJING results show little dependence on centrality.

To account for possible changes of $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ due to possible changes in $\langle\langle p_t\rangle\rangle$ with incident energy and/or centrality of the collision, we also study the square root of the measured correlations scaled by $\langle\langle p_t\rangle\rangle$. The resulting quantity $\sqrt{\langle\Delta p_{t,i}\Delta p_{t,j}\rangle}/\langle\langle p_t\rangle\rangle$ is shown in Fig. 4 for Au+Au collisions at 20, 62, 130, and 200 GeV. Similar results from Pb+Pb collisions at 17 GeV [16] are also shown in Fig. 4. These values are consistent with our measured results for Au+Au at 20 GeV. We observe little or no dependence on the incident energy for this quantity. The inset in Fig. 4 demonstrates the incident energy dependence of $\sqrt{\langle\Delta p_{t,i}\Delta p_{t,j}\rangle}/\langle\langle p_t\rangle\rangle$ for the 0 - 5% most central bin where the Pb+Pb results are from Ref. [16].

In contrast to the measured correlations, HIJING predictions for $\sqrt{\langle\Delta p_{t,i}\Delta p_{t,j}\rangle}/\langle\langle p_t\rangle\rangle$ vary with incident energy. HIJING predicts a different centrality dependence as well as a noticeable dependence on the incident energy.

In conclusion we observe clear non-zero p_t correlations, $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$, in Au+Au collisions from $\sqrt{s_{NN}}$ = 20 to 200 GeV. The quantity $\frac{dN}{d\eta}\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ increases with beam energy. The centrality dependence of $\frac{dN}{d\eta}\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ may show signs of effects such as thermalization [15], the onset of jet suppression [14, 24], the saturation of transverse expansion in central collisions [35], or other processes. The quantity $\sqrt{\langle\Delta p_{t,i}\Delta p_{t,j}\rangle}/\langle\langle p_t\rangle\rangle$ shows little or no change with beam energy. HIJING model calculations underpredict the measured correlations and do not predict the observed centrality dependence.

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