

## Measurement of Nonrandom Event-by-Event Fluctuations of Average Transverse Momentum in $\sqrt{s_{NN}} = 200$ GeV Au + Au and $p + p$ Collisions

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Event-by-event fluctuations of the average transverse momentum of produced particles near mid-rapidity have been measured by the PHENIX Collaboration in  $\sqrt{s_{NN}} = 200$  GeV Au + Au, and  $p + p$  collisions at the Relativistic Heavy Ion Collider. The fluctuations are observed to be in excess of the expectation for statistically independent particle emission for all centralities. The excess fluctuations exhibit a dependence on both the centrality of the collision and on the  $p_T$  range over which the average is calculated. Both the centrality and  $p_T$  dependence can be well reproduced by a simulation of random particle production with the addition of contributions from hard-scattering processes.

The measurement of fluctuations in the event-by-event average transverse momentum of produced particles in relativistic heavy ion collisions has been proposed as a probe of phase instabilities near the QCD phase transition [1–3], which could result in classes of events with different properties, such as the effective temperature of the collision. Fluctuation measurements could also provide information about the onset of thermalization in the system [4]. The resulting phenomena can be observed by measuring deviations of the event-by-event average  $p_T$ , referred to here as  $M_{p_T}$ , of produced charged particles from the expectation for statistically independent particle emission [5,6] after subtracting contributions from fluctuations arising from physical processes such as elliptic flow and jet production.

Several  $M_{p_T}$  fluctuation measurements have been reported in heavy ion collisions [7–10], including a study by PHENIX [9] in  $\sqrt{s_{NN}} = 130$  GeV Au + Au collisions, which set limits on the magnitude of nonrandom fluctuations in  $M_{p_T}$ . Recently, STAR has reported fluctuations in excess of the random expectation, within the PHENIX limits, at the same collision energy [10]. For the first results from  $\sqrt{s_{NN}} = 200$  GeV Au + Au and  $p + p$  collisions reported here, upgrades of the PHENIX central arm spectrometers [11] have expanded the azimuthal acceptance from  $58.5^\circ$  to  $180.0^\circ$  within the pseudorapidity range of  $|\eta| < 0.35$ . Pad chamber and calorimeter detectors have also been utilized for improved background rejection. As a result, the sensitivity of the PHENIX spectrometer to the observation of fluctuations in  $M_{p_T}$  due to event-by-event fluctuations in the effective temperature [9,12] has improved by greater than a factor of 2.

Minimum bias events triggered by a coincidence between the zero degree calorimeters (ZDC) and the beam-beam counters (BBC), with a requirement that the collision vertex, which is measured with an rms resolution of less than 6 mm in central collisions and 8 mm in the most peripheral collisions, be within 5 cm of the nominal origin, are used in this analysis. Event centrality for Au + Au collisions, which is defined using correlations in the BBC and ZDC analog response [13], is divided into several classes, each containing an average of 244 000 analyzed events. These classes are associated to the estimated average number of participants in the collision,  $\langle N_{\text{part}} \rangle$ , which is derived using a Glauber model Monte Carlo calculation with the BBC and ZDC detector response taken into account [14].

Charged particle momenta are reconstructed in the PHENIX central arm spectrometers with a drift chamber and a radially adjacent pixel pad chamber. Nonvertex track background rejection is provided by pixel pad chambers and calorimeters located further outward radially from the collision vertex [15]. The momentum resolution is  $(\delta p/p) \approx 0.7\% \oplus 1.0\% \times p$  (GeV/c).

$M_{p_T}$  is calculated for each event, which contains a number of reconstructed tracks within a specified  $p_T$

range,  $N_{\text{tracks}}$ . The  $p_T$  range is always given a lower bound of 200 MeV/c and a varying upper bound,  $p_T^{\text{max}}$ , from 500 MeV to 2.0 GeV/c. There is a minimum  $N_{\text{tracks}}$  cut of three in both Au + Au events (removing 0%, 4.6%, and 29% of events in the 0%–50%, 50%–60%, and 60%–70% centrality ranges, respectively, when  $p_T^{\text{max}} = 2.0$  GeV/c) and  $p + p$  events (removing 59% of the events).

There are several measures by which the magnitude of nonrandom fluctuations can be quantified, namely  $\phi_{p_T}$  [16,17],  $\nu_{\text{dynamic}}$  [18], and  $F_{p_T}$  [9]. The calculation of  $F_{p_T}$  is based upon the magnitude of the fluctuation,  $\omega_{p_T}$ , defined as

$$\omega_{p_T} = \frac{(\langle M_{p_T}^2 \rangle - \langle M_{p_T} \rangle^2)^{1/2}}{\langle M_{p_T} \rangle} = \frac{\sigma_{M_{p_T}}}{\langle M_{p_T} \rangle}. \quad (1)$$

$F_{p_T}$  is defined as the fractional deviation of  $\omega_{p_T}$  from a baseline estimate defined using mixed events,

$$F_{p_T} = \frac{[\omega_{(p_T, \text{data})} - \omega_{(p_T, \text{mixed})}]}{\omega_{(p_T, \text{mixed})}}. \quad (2)$$

Mixed event  $M_{p_T}$  distributions are validated by comparisons to a calculation of  $M_{p_T}$  assuming statistically independent particle emission using parameters extracted from the inclusive  $p_T$  distributions of the data [19]. For the 0%–5% centrality class, which suffers the most from tracking inefficiency, the effects of two-track resolution, and background contributions, the mixed event  $M_{p_T}$  distribution yields a value of  $F_{p_T} = 0.04\%$  with respect to the calculation. The results of this comparison are included in the estimates of the systematic errors. Further details on the mixed event procedure and a discussion of contributions to the value of  $F_{p_T}$  from detector efficiency and resolution effects can be found in the description of the data analysis of  $\sqrt{s_{NN}} = 130$  GeV Au + Au collisions [9].

Comparisons of the data and mixed event  $M_{p_T}$  distributions for the 0%–5% and 30%–35% centrality classes are shown in Fig. 1. Any excess fluctuations are small and are difficult to distinguish by eye in a direct overlay of the  $M_{p_T}$  distributions. Therefore, the comparison is also shown as residuals of the difference between the data and mixed event distributions in units of standard deviations of the individual data points. The double-peaked shape in the residual distributions is an artifact of the fact that the mixed event distributions, which always have a smaller standard deviation in  $M_{p_T}$  than the data, are normalized to minimize the total  $\chi^2$  of the residual distribution.

Figure 2 shows the magnitude of  $F_{p_T}$ , expressed in percent, as a function of centrality for Au + Au collisions with  $p_T^{\text{max}} = 2.0$  GeV/c. The error bars are dominated by time-dependent systematic effects during the data taking period due to detector variations, which are minimized using strict time-dependent cuts on the mean and standard deviations of the inclusive  $p_T$  and  $N_{\text{tracks}}$

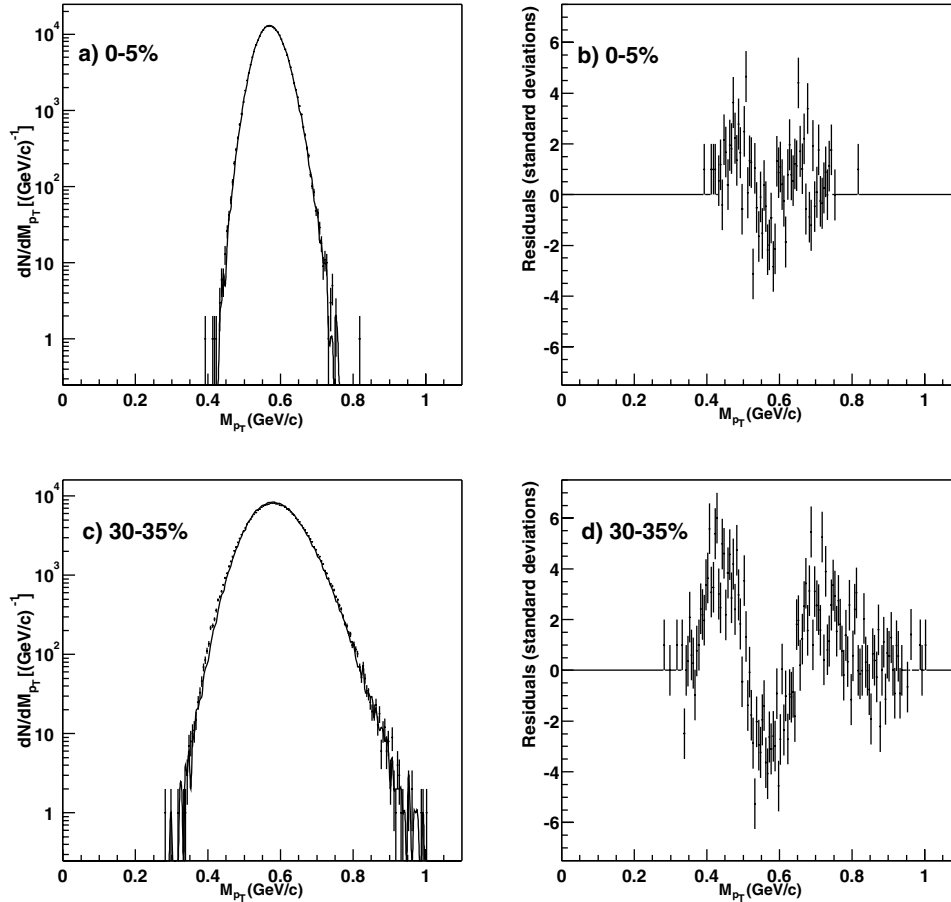


FIG. 1. Comparisons between the data and mixed event  $M_{p_T}$  distributions for the representative 0%–5% and 30%–35% centrality classes. Plots (a) and (c) show direct comparisons of the data (points) and normalized mixed event (solid line)  $M_{p_T}$  distributions. Plots (b) and (d) show the residuals between the data and mixed events in units of standard deviations of the data points from the mixed event points.

distributions. Statistical errors are below  $F_{p_T} = 0.05\%$  for all centralities. The systematic errors are determined by dividing the entire dataset into ten separate subsets for each centrality class and extracting the standard deviation of the  $F_{p_T}$  values calculated for each subset. From Fig. 2, a significant nonrandom fluctuation is seen that appears to peak in midcentral collisions. However, the magnitude of the observed fluctuations are within previously published limits [9]. In addition, the value of  $F_{p_T}$  for the most peripheral Au + Au collisions is consistent with, albeit slightly below, the value measured by the same PHENIX apparatus in minimum bias  $\sqrt{s_{NN}} = 200$  GeV  $p + p$  collisions. If the magnitude of  $F_{p_T}$  is entirely due to fluctuations in the effective temperature of the system [12], this measurement corresponds to a fluctuation of  $\sigma_T/\langle T \rangle = 1.8\%$  at 0%–5% centrality and 3.7% at 20%–25% centrality.

To further understand the source of the nonrandom fluctuations,  $F_{p_T}$  is measured over a varying  $p_T$  range for which  $M_{p_T}$  is calculated,  $0.2 \text{ GeV}/c < p_T < p_T^{\text{max}}$ . Figure 3 shows  $F_{p_T}$  plotted as a function of  $p_T^{\text{max}}$  for the 20%–25% centrality class. A trend of increasing  $F_{p_T}$  for

increasing  $p_T^{\text{max}}$  is observed for this and all other centrality classes. The majority of the contribution to  $F_{p_T}$  appears to be due to correlations of particles with  $p_T > 1.0 \text{ GeV}/c$ , where  $F_{p_T}$  increases disproportionately to the small increase (only 14%) of  $N_{\text{tracks}}$  in this region.

The behavior of  $F_{p_T}$  as a function of centrality and  $p_T$  is similar to trends seen in measurements of elliptic flow [20]. The contribution of elliptic flow to the magnitude of  $F_{p_T}$  is investigated using a Monte Carlo simulation whereby events are generated with a Gaussian distribution of  $N_{\text{tracks}}$  particles determined by a fit to the data and a random reaction plane azimuthal angle,  $\Phi$ , between 0 and  $2\pi$ . Independent particles within an event are generated following the inclusive  $p_T$  distribution with azimuthal angles,  $\phi$ , distributed according to collective elliptic flow described by the function  $[dN/d(\phi - \Phi)] = 1 + 2v_2 \cos[2(\phi - \Phi)]$ . The values of the  $v_2$  parameter are linearly parametrized as a function of  $p_T$  and centrality using PHENIX measurements of inclusive charged hadrons [20]. Only generated particles that lie within the PHENIX azimuthal acceptance are included in the calculation of  $M_{p_T}$ . This simulation estimates that the

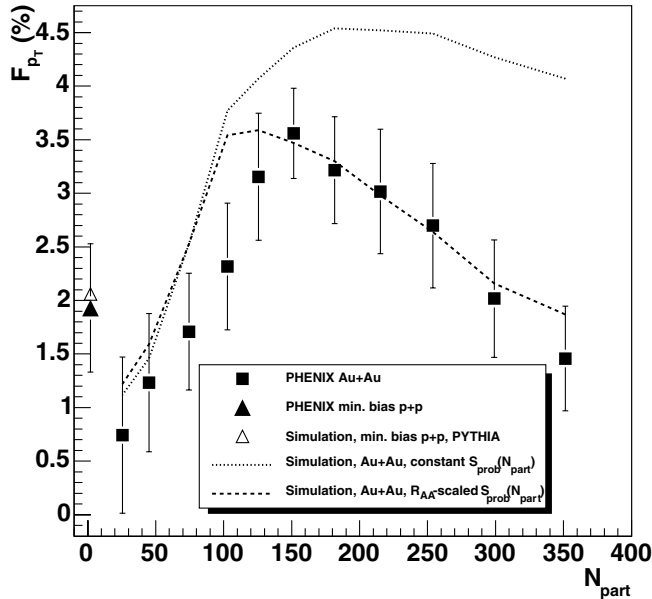


FIG. 2.  $F_{p_T}$  (in percent,  $0.2 \text{ GeV}/c < p_T < 2.0 \text{ GeV}/c$ ) as a function of centrality, which is expressed in terms of the number of participants in the collision,  $N_{\text{part}}$ . The solid squares represent the Au + Au data. The solid triangle represents the minimum bias  $p + p$  data point. The open triangle is the result from an analysis of PYTHIA minimum bias  $p + p$  events within the PHENIX acceptance. The error bars include statistical and systematic errors and are dominated by the latter. The curves are the results of a Monte Carlo simulation with hard processes modeled using PYTHIA with a constant (dotted curve) and  $R_{AA}$ -scaled (dashed curve) hard-scattering probability factor, and include the estimated contribution due to elliptic flow.

contribution of elliptic flow to  $F_{p_T}$  is largely canceled out by the symmetry of the PHENIX acceptance, and is negligible for central collisions. The estimated elliptic flow contribution to the value of  $F_{p_T}$  is less than 0.1% for  $N_{\text{part}} > 150$ , increasing to about 0.6% for  $N_{\text{part}} < 100$ . Note that  $F_{p_T}$  measured for minimum bias  $p + p$  collisions, where collective flow is not expected to contribute, is nonzero ( $1.9 \pm 0.6\%$ ), implying that a nonflow contribution may also be present in peripheral Au+Au collisions.

Figure 3 illustrates that a large contribution to the observed nonrandom fluctuations is due to the correlation of high  $p_T$  particles, such as might be expected from correlations due to jet production [21]. In order to estimate the contribution due to jets, a Monte Carlo simulation is again applied. Events are generated with a Gaussian distribution of  $N_{\text{tracks}}$  particles as independent particles that follow an  $m_T$  exponential fit to the inclusive data  $p_T$  distribution. Hard processes are defined to occur at a uniform rate per generated particle,  $S_{\text{prob}}(N_{\text{part}})$ , for each centrality class. This is the only parameter that is allowed to vary in the simulation. As Au + Au events are being generated, single  $\sqrt{s_{NN}} = 200 \text{ GeV}$   $p + p$  hard-

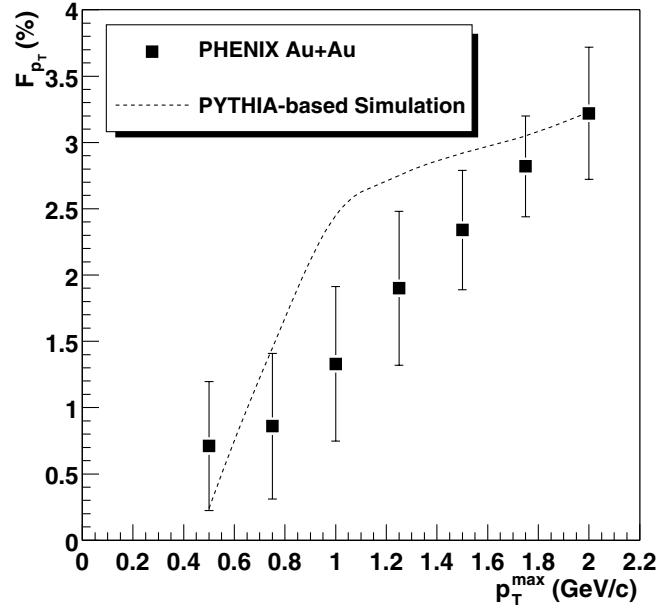


FIG. 3.  $F_{p_T}$  (in percent) of nonrandom fluctuations as a function of the  $p_T$  range over which  $M_{p_T}$  is calculated,  $0.2 \text{ GeV}/c < p_T < p_T^{\text{max}}$ , for the 20%–25% centrality class ( $N_{\text{part}} = 181.6$ ). The curve is the result of a Monte Carlo simulation with hard-scattering processes modeled using PYTHIA with  $S_{\text{prob}}(N_{\text{part}}) = 0.075$  and  $R_{AA} = 0.41$  [23]. The error bars include statistical and systematic errors and are dominated by the latter. The contribution of elliptic flow is estimated to be negligible at this centrality.

scattering events generated by the PYTHIA event generator [22] and filtered by the PHENIX acceptance are embedded into the event. The addition of the PYTHIA events affects the mean and standard deviation of the inclusive  $p_T$  spectra by less than 0.1%. The value of  $F_{p_T}$  has been extracted from 100 000 PYTHIA events for minimum bias  $p + p$  collisions, yielding  $F_{p_T} = 2.06\%$  within the PHENIX acceptance, which is consistent with the measured value of  $F_{p_T} = 1.9 \pm 0.6\%$ .

Two scenarios are considered for studies of the centrality dependence of jet contributions to the value of  $F_{p_T}$ : (i) with  $S_{\text{prob}}(N_{\text{part}})$  set at a constant rate for all centrality classes, and (ii) with  $S_{\text{prob}}(N_{\text{part}})$  scaled for each centrality class by the PHENIX measurement of the suppression of high  $p_T$  charged particles, which is characterized by the nuclear modification factor,  $R_{AA}$ , integrated over  $p_T > 4.5 \text{ GeV}/c$  [23]. The  $p_T$  value at which  $R_{AA}$  is extracted has little effect on the simulation results, which change by less than 0.2% for 0%–5% centrality if the  $R_{AA}$  measurement at  $p_T = 2.0 \text{ GeV}/c$  is used instead. The latter scenario is intended to model the effect of the suppression of jets due to energy loss in the nuclear medium [24] on the fluctuation signal. The initial value of  $S_{\text{prob}}(N_{\text{part}})$  for both scenarios is normalized so that the  $F_{p_T}$  result from the  $R_{AA}$ -scaled simulation matches that of the data for the 20%–25% centrality class. The results of the simulation

as a function of  $p_T^{\max}$ , with  $S_{\text{prob}}(N_{\text{part}})$  scaled by  $R_{AA}$ , are represented by the dashed curve in Fig. 3 for the 20%–25% centrality class. The trend of increasing  $F_{p_T}$  with increasing  $p_T^{\max}$  observed in the data is reproduced by the simulation reasonably well.

The results of the two hard-scattering simulation scenarios are shown in Fig. 2 as a function of centrality. The model curves include the small contribution estimated from the elliptic flow simulation. The dotted curve is the result with  $S_{\text{prob}}(N_{\text{part}})$  fixed for all centralities. The dashed curve is the result with  $S_{\text{prob}}(N_{\text{part}})$  scaled by  $R_{AA}$  as a function of centrality. Within this simulation, the decrease of  $F_{p_T}$  for the more peripheral events is explained as a decrease in the signal strength relative to number fluctuations from the small and decreasing value of  $N_{\text{tracks}}$ . If  $S_{\text{prob}}(N_{\text{part}})$  remains constant, the value of  $F_{p_T}$  decreases only slightly when going from midcentral to central collisions, in contradiction with the large decrease seen in the data over this centrality range. When  $S_{\text{prob}}(N_{\text{part}})$  is scaled by  $R_{AA}$  as a function of centrality, the trend in the simulation of decreasing  $F_{p_T}$  with increasing centrality is more consistent with the data.

To summarize, the PHENIX experiment has observed a positive nonrandom fluctuation signal in event-by-event average transverse momentum, measured as a function of centrality and  $p_T$  in  $\sqrt{s_{NN}} = 200$  GeV Au + Au and  $p + p$  collisions. The increase of  $F_{p_T}$  with increasing  $p_T$  implies that the majority of the fluctuations are due to correlated high  $p_T$  particles. A Monte Carlo simulation that includes elliptic flow and a PYTHIA-based hard-scattering description can consistently describe contributions to the signal as a function of centrality and  $p_T$  with a simple implementation of jet suppression.

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