Probing the bulk medium in relativistic heavy ion collisions using two-particle correlations

R L Ray for the STAR Collaboration
Department of Physics, The University of Texas at Austin, Austin, TX 78712, USA
E-mail: ray@physics.utexas.edu

Abstract. Measurements of charge-independent and charge-dependent two-particle correlations for Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV from the STAR experiment are presented as functions of transverse momentum $p_t$ and difference variables $\eta_1 - \eta_2$ (pseudorapidity) and $\phi_1 - \phi_2$ (azimuth) for final state hadrons with $0.15 \leq p_t \leq 2$ GeV/c, $|\eta| \leq 1.3$ and full $2\pi$ azimuth. Significant large-momentum-scale correlation structures are observed which were not seen in similar studies at lower energy and are not predicted by theoretical collision models. Charge-independent correlations at $p_t > 0.5$ GeV/c and small $\eta, \phi$ differences are observed which are consistent with a scenario in which initial-state semi-hard (low-$Q^2$) parton scattering and fragmentation are modified by in-medium dissipation resulting in event-wise mean-$p_t$ fluctuations and significant broadening of the same-side correlation peak on $\eta_1 - \eta_2$ by a factor 2.3 from peripheral to central collisions. Charge-dependent correlations on $(\eta, \phi)$ difference variables indicate the evolution of hadron emission geometry with increasing centrality from one-dimensional fragmentation of longitudinal color strings to two-dimensional $(\eta, \phi)$ fragmentation of a hadron-opaque bulk medium. The new correlation methods presented here permit quantitative study of the nonperturbative interactions between low-$Q^2$ partons and the bulk medium produced in relativistic heavy ion collisions.

1. Introduction
Analysis of two-particle correlations and associated nonstatistical fluctuations of event-wise observables in relativistic heavy ion collisions may ultimately reveal the dynamics of parton scattering and hadronization as well as physical properties [1, 2, 3] of the hot, dense medium produced at the Relativistic Heavy Ion Collider (RHIC). The first measurements at RHIC demonstrated that substantial non-statistical fluctuations occur in the event-wise $\langle p_t \rangle$ of charged particles from Au-Au collisions [4, 5] which are qualitatively larger than those reported at the CERN Super Proton Synchrotron (SPS) with one-tenth the CM energy [6, 7]. It is hypothesized [4, 5] that these fluctuations result mainly from incompletely equilibrated initial-state multiple scattering [8] or minimum-biased, semi-hard (low-$Q^2$) parton scattering [9], where the increased hard (pQCD)-scattering cross section at RHIC energies produces larger two-particle correlations. Variance measures of nonstatistical fluctuations are proportional to integrals over two-particle correlations. Studies of the latter facilitate interpretation of event-wise fluctuations in terms of underlying dynamical processes in which the medium affects the semi-hard scattering of partons and the hadronization process and, in turn, the bulk medium responds to those semi-hard scattered partons.

In order to carry out the above program it is essential to have accurate “probes” which are
provided by correlation measurements for minimum-bias proton - proton (p-p) collisions [10] at CM energy similar to that for each colliding nucleon-nucleon pair in Au-Au. Charge independent correlations on transverse rapidity [10] \((y_{t1} \times y_{t2})\) reveal a semi-hard scattering structure peaked at approximately \(p_t \sim 1\) GeV/c; projections onto difference variables \((\eta_1 - \eta_2, \phi_1 - \phi_2)\) display a characteristic same-side \((|\phi_1 - \phi_2| < \pi/2)\) “jet-like” peak at small relative pair opening angle with a broad (on \(\eta_1 - \eta_2\) away-side \((|\phi_1 - \phi_2| > \pi/2)\) ridge peaked at \(|\phi_1 - \phi_2| = \pi\) as expected for back-to-back jets. At lower \(p_t\) (< 0.5 GeV/c) charge-ordering on \((\eta_1 - \eta_2)\) and enhanced back-to-back \((|\phi_1 - \phi_2| = \pi)\) unlike charge-sign pair correlations are observed as expected for longitudinal (beam axis) color-string fragmentation with local charge and transverse momentum conservation. These results are consistent with the two-component model for high energy hadron-hadron collisions in which particle production occurs primarily by longitudinal color-string fragmentation with occasional semi-hard transverse parton scattering and fragmentation into final state hadrons. The evolution of these elementary structures with increasing centrality is shown for Au-Au collisions at \(\sqrt{s_{NN}} = 130\) GeV [11, 12, 13]. Similar results from STAR for Au-Au collisions at \(\sqrt{s_{NN}} = 62\) GeV are discussed.

2. Experiment

Data for this analysis (Au-Au at 130 GeV) were obtained with the STAR detector [14] using a 0.25 T uniform magnetic field parallel to the beam axis. A minimum-bias event sample required coincidence of two Zero-Degree Calorimeters (ZDC); a 0-15% of total cross section event sample was defined by a threshold on the Central Trigger Barrel (CTB), with ZDC coincidence. Event triggering and charged-particle measurements with the Time Projection Chamber (TPC) are described in [14]. Tracking efficiencies, event and track quality cuts and primary-particle definition are described in [4, 15]. Charged particles were accepted in \(|\eta| \leq 1.3\), full azimuth, and \(0.15 \leq p_t \leq 2\) GeV/c. Particle identification was not implemented but charge sign was determined. Corrections were made for two-track inefficiencies due to merging and intersecting trajectories by applying two-track proximity cuts in the TPC to both real and mixed-event pairs. Small momentum scale correlation (SSC) structures due to quantum, Coulomb and strong-interaction correlations \([16]\) were suppressed by eliminating real and mixed-event track pairs (<22% of total) when \(|\eta_\Delta|, |\phi_\Delta|\) and \(|p_{t1} - p_{t2}|\) were respectively less than 0.3, \(\pi/6\) and 0.15 GeV/c for charge independent (1.0, 1.0 and 0.2 GeV/c for charge dependent) correlations if \(p_t < 0.8\) GeV/c for either particle. Those cuts do not significantly affect the correlation structures shown here. Four centrality classes for 300k events for the 130 GeV data, labeled (a) - (d) for central to peripheral, respectively, in the following were defined by cuts on TPC track multiplicity \(N\) within the acceptance relative to minimum-bias event multiplicity frequency distribution end-point \(N_0\) [4, 17]. The four centrality classes assumed here were defined by (d) \(0.03 < N/N_0 \leq 0.21\), (c) \(0.21 < N/N_0 \leq 0.56\), (b) \(0.56 < N/N_0 \leq 0.79\) and (a) \(N/N_0 > 0.79\).

3. Correlation measurement quantities

The two-particle correlation function and pair-number density-ratio distribution are defined by

\[
C(\vec{p}_1, \vec{p}_2) \equiv \rho_{\text{sib}}(\vec{p}_1, \vec{p}_2) - \rho_{\text{mix}}(\vec{p}_1, \vec{p}_2) = \rho_{\text{mix}}(\vec{p}_1, \vec{p}_2) [r(\vec{p}_1, \vec{p}_2) - 1]
\]

\[
r(\vec{p}_1, \vec{p}_2) \equiv \rho_{\text{sib}}(\vec{p}_1, \vec{p}_2)/\rho_{\text{mix}}(\vec{p}_1, \vec{p}_2),
\]

where \(\rho_{\text{sib}}(\vec{p}_1, \vec{p}_2)\) is the object distribution comprised of particle pairs from single events (sibling pairs) and the reference distribution, \(\rho_{\text{mix}}(\vec{p}_1, \vec{p}_2)\), consists of pairs formed by sampling each particle of the pair from two different but similar events (mixed-event pairs). In order to visualize the full correlation structure projections onto subspaces \((p_{t1} vs p_{t2}), (\eta_1 vs \eta_2)\) and \((\phi_1 vs \phi_2)\) are constructed. Those results, discussed below, indicate that the principle dependences are on \((p_{t1} + p_{t2}), (p_{t1} - p_{t2})\), and the differences \(\eta_\Delta \equiv \eta_1 - \eta_2\) and \(\phi_\Delta \equiv \phi_1 - \phi_2\). For the
latter the correlation distributions are projected onto the two difference variables \( \phi_\Delta \) and \( \eta_\Delta \) which is referred to as a joint autocorrelation. An autocorrelation is a projection by averaging from subspace \((x_1, x_2)\) onto difference variable \( x_\Delta \equiv x_1 - x_2 \) \([18]\). A joint autocorrelation is a simultaneous projection onto two difference variables.

Sibling and mixed-event pair-number densities \( \rho(\vec{p}_1, \vec{p}_2) \) for four charge-pair combinations \((++, +-, --, -+\) were projected onto \((p_{t1}, p_{t2}), (\eta_1, \eta_2), (\phi_1, \phi_2)\) and \((\eta_\Delta, \phi_\Delta)\). This was done by filling histograms of number of pairs \( n_{ij} \) \( \equiv \epsilon_x \epsilon_y \rho(x_i, y_j) \) where subscripts \( ij \) denote the two-dimensional (2D) bin indices and \( \epsilon_x, \epsilon_y \) are histogram bin widths on variables \( x, y \in \{\eta_1, \eta_2, \phi_1, \phi_2, \eta_\Delta, \phi_\Delta\} \). Sibling and mixed-event pair number histograms for each charge-pair combination were separately normalized to the total number of detected pairs in each centrality class: \( \bar{n}_{ij,sib} = n_{ij,sib}/\sum_{ij} n_{ij,sib} \) and \( \bar{n}_{ij,mix} = n_{ij,mix}/\sum_{ij} n_{ij,mix} \). Normalized pair-number ratios \( r_{ij} = \bar{n}_{ij,sib}/\bar{n}_{ij,mix} \) are the basis for the present analysis. To reduce systematic error ratio histograms were obtained for subsets of events within a given centrality class which have similar multiplicities (differences \( \leq 50\) and primary collision vertex locations within the detector (within 7.5 cm along the beam axis). Ratios \( r_{ij} \) were defined as weighted (by total number of sibling pairs) over all subsets in each centrality class. Ratios were further combined to form like-sign (LS: ++, --), unlike-sign (US: +-, -+), charge-independent (CI = LS + US), and charge-dependent (CD = LS - US) ratios. The present sign convention for CD \([4]\) is compatible with standard particle physics isospin convention.

4. **Charge independent correlations on \( p_{t1} \) versus \( p_{t2} \)**

The centrality dependence of differential quantity \( r - 1 \) in 2D transverse momentum subspace \([11]\) is shown in Fig. 1. Charge independent pair ratios \( r \) were binned on \( p_t \) using variable bin sizes in order to achieve approximately uniform pair statistics throughout the acceptance. The variable \( p_t \) bin sizes are defined by uniform bins on quantity \( X(p_t) \equiv 1 - \exp\{- (m_t - m_\pi)/0.4 \text{ GeV}\} \) \((m_t = \sqrt{p_t^2 + m_\pi^2}, \text{ pion mass } m_\pi \text{ assumed})\), \( 0 \leq X \leq 1 \), with bin size 1/25. SSC attributed to quantum correlations (HBT) and Coulomb interactions produce peaks at low-\(X(p_t)\) and along the diagonal from \((0,0)\) to \((1,1)\) based on MC simulations \([16, 19]\). Per-bin statistical errors for \( r - 1 \) in Fig. 1 are \( \sim 15\% \) of the maximum correlation amplitude for each centrality. Systematic errors \([4]\) are dominated by contamination from non-primary background particles, mainly weak-decay daughters \([15]\), and varied from \( \pm 7\% \) for \( X(p_{t1,2}) > 0.4 \) up to \( \pm 16\% \) for \( X(p_{t1,2}) < 0.4 \) and \( \pm 12\% \) in the off-diagonal corners.

The dominant features in Fig. 1 are 1) a large-momentum-scale correlation (LSC) ‘saddle’ structure with positive (negative) curvature along the \( X(p_t)_{\Sigma(\Delta)} = X(p_{t1}) + (-)X(p_{t2}) \) sum (difference) direction and 2) a narrow peak structure at large \( X(p_t) \) \((p_t > 0.6 \text{ GeV}/c)\). With increasing centrality the negative curvature of the LSC saddle along the difference variable \((i.e. \text{ from } (0,1) \text{ to } (1,0))\) increases in absolute magnitude, the positive curvature along the \((0,0) \text{ to } (1,1))\) diagonal decreases, and the magnitude of the peak at large \( X(p_t) \) also decreases. The first (saddle shape) will be shown to be consistent with fluctuating local temperature and/or velocity \((\text{effective temperature})\), either from event-to-event or internally within each event. The second feature \((\text{large-}X(p_t)\text{ peak})\) is assumed to result from semi-hard scattering correlations as observed in p-p collisions \([10]\). An analytic model based on fluctuating effective temperature quantitatively describes the saddle-shape feature of the data.

An equilibrated system is described by global temperature parameter \( \beta_0 \equiv 1/T_0 \). However, if the system (one collision event) is partially equilibrated the local velocity/temperature varies on \( \eta, \phi \) for each event according to some unknown distribution \( \beta(\eta, \phi) \). The latter distribution may itself vary from event-to-event, for example as localized “hot spots” randomly appear at different \( \eta, \phi \). Distribution \( \beta(\eta, \phi) \) determines the range and probability of shapes of the effective local-parent \( p_t \) spectra \( \exp\{-\beta(\eta, \phi)(m_t - m_\pi)\} \) sampled in each event by the final-state hadrons. Fluctuations in \( \beta \) linearly represent fluctuations in \( 1/T \) and/or \( v/c \) of the local-
parent \( p_t \) spectra. Each particle in each event samples a particular value of \( \beta \). If the resulting distribution of \( \beta \) values for an event ensemble is represented by \( g_1(\beta) \), with centroid \( \beta_0 \) and variance \( \sigma_\beta^2 \), the inclusive \( p_t \) spectrum can be calculated by convoluting a thermal spectrum \( e^{-\beta(m_t-m_\pi)} \) with \( g_1(\beta) \). For example, if \( g_1(\beta) \) is modeled by a gamma distribution [20] then

\[
1/p_t dN/dp_t = A/\left(1 + \beta_0(m_t - m_\pi)/n\right)^n,
\]

a Lévy distribution [21]. Exponent \( 1/n = \sigma_\beta^2/\beta_0^2 \) is the relative variance of \( g_1(\beta) \).

By similar argument a pair of hadrons (with labels 1 and 2) samples local-parent two-particle \( p_t \) spectrum \( e^{-\beta_1(m_{t1}-m_\pi)}e^{-\beta_2(m_{t2}-m_\pi)} \). The histogram of sampled \( (\beta_1, \beta_2) \) values for an ensemble of hadron pairs from many events can be described by a two-dimensional (2D) temperature/velocity distribution \( g_2(\beta_1, \beta_2) \). If \( g_2(\beta_1, \beta_2) \) is modeled by a 2D gamma distribution with arbitrary covariance (i.e. product of independent distributions on \( \beta_2 \equiv \beta_1 + \beta_2 \) and \( \beta_\Delta \equiv \beta_1 - \beta_2 \) respectively), the two-particle \( (p_{t1}, p_{t2}) \) spectrum is well approximated by 2D Lévy model distribution

\[
F_{\text{mix}} \propto \left(1 + \frac{\beta_0 m_t}{2n_\Sigma}\right)^{-2n_\Sigma} \left[1 - \left(\frac{\beta_0 m_\Delta}{2n_\Delta + \beta_0 m_{t\Sigma}}\right)^2\right]^{-n_\Delta}
\]

on sum and difference variables \( m_{t\Sigma} \equiv m_{t1} + m_{t2} - 2m_\pi \) and \( m_{t\Delta} \equiv m_{t1} - m_{t2} \). Parameters \( 1/n_\Sigma \) and \( 1/n_\Delta \) are relative variances of \( g_2(\beta_1, \beta_2) \) along sum and difference variables \( \beta_\Sigma \) and \( \beta_\Delta \) respectively, and \( \Delta(1/n)_{\text{tot}} \equiv 1/n_\Sigma - 1/n_\Delta \) is the relative covariance [22] of \( g_2(\beta_1, \beta_2) \) measuring the integrated velocity/temperature correlations. Mixed-pair distribution \( F_{\text{mix}}(p_{t1}, p_{t2}) \), a product of two single-particle Lévy distributions, has the form of Eq. (2) but with \( n_\Sigma = n_\Delta = n \) (\( g_2 \) has zero covariance). Ratio \( r_{\text{model}} \equiv F_{\text{mix}}/F_{\text{mix}} \) was used to fit the data in Fig. 1.

Data in Fig. 1 (excluding peak region with \( X(p_t)_\Sigma > 1.6 \)) were fitted with \( r_{\text{model}} = 1 + C \) by varying parameters \( n_\Sigma, n_\Delta \) and \( C \) (offset). Parameter \( \beta_0 = 5 \text{ GeV}^{-1} \) is fixed by the inclusive \( p_t \) distribution for \( p_t < 1 \text{ GeV}/c \). Two-dimensional saddle-fit residuals are independent of difference \( X(p_t)_\Delta = X(p_{t1}) - X(p_{t2}) \); the Lévy temperature fluctuation model adequately describes the saddle structure. Residuals from the fit for mid-central events (b) (typical) are shown in Fig. 2 (left panel) projected onto sum variable \( X(p_t)_\Sigma \). This residual structure is possibly due to semi-hard parton scattering [10, 23]. The centrality dependences on mean binary collisions per participant \( \nu \) [17] of efficiency-corrected (factor \( S \)) per-particle model parameters \( S N \Delta(1/n) \) [24] which determine the saddle shape amplitudes in Fig. 1 are shown in Fig. 2 (right panel) and listed in Table 1. The linearity of these results supports the hypothesis that the low \( p_t \) correlation components of the bulk medium are responding proportionally to the per-event frequency of semi-hard partonic scattering (binary collision scaling) via momentum...
dissipation. We also observe the following in the right panel of Fig. 2: a) reduced curvature along the sum direction and b) increased curvature along the difference direction which may represent respectively transport of semi-hard parton structure to lower $p_t$ and a more correlated bulk medium. RQMD [25] and HIJING [9] predict saddle-shape correlations. However in both cases the predictions differ qualitatively from the data [11].

5. Charge-independent correlations on $\eta_\Delta$ versus $\phi_\Delta$

If correlation structure is invariant on sum variables $\eta_1 + \eta_2$ and $\phi_1 + \phi_2$, as in these heavy ion collisions [13], distributions $\tilde{r}$ can be projected along those sum variables to form one-dimensional (1D) autocorrelations on corresponding difference variables without information loss. Plotted in Fig. 3 are perspective views of CI joint autocorrelations $\bar{N}(\tilde{r} - 1)$ measuring number of correlated particle pairs per final state particle, where $\bar{N}$ is the mean multiplicity in the acceptance. The distributions are dominated by 1) a 1D quadrupole component $\propto \cos(2\phi_\Delta)$ conventionally attributed to elliptic flow; 2) a 1D dipole component $\propto \cos(\phi_\Delta)$ associated with transverse momentum conservation for parton scattering and bulk hadronization, and 3) a 2D ‘same-side’ ($|\phi_\Delta| < \pi/2$) peak, which is the principal object of interest here, and assumed to be associated with low-$Q^2$ scattered parton fragmentation.

Back-to-back ($\phi_\Delta \sim \pi$) azimuth correlations from momentum conservation are expected in hard parton scattering. However, at low $p_t$ the away-side di-jet structure is broad, and indistinguishable from the dipole $\cos(\phi_\Delta)$ component describing two-particle transverse momentum conservation in the bulk system. Dipole and quadrupole $\cos(2\phi_\Delta)$ components were subtracted from distributions in Fig. 3 to obtain those in Fig. 4 by minimizing residuals on the away side for $|\phi_\Delta| > \pi/2$ and $|\eta_\Delta| \sim 2$. The resulting away-side hemicylinder in Fig. 4 is featureless, even for the most peripheral collisions shown here. If longitudinal color-string fragmentation [26] remained dynamically relevant we would expect in this $p_t$ interval significant correlation structure on the away side of Fig. 4: a prominent gaussian on $\eta_\Delta$ due to local charge conservation as observed in p-p collisions [23, 27]. Lack of such structure suggests that longitudinal strings are not significant in A-A collisions, even for the most peripheral collisions in this study (Fig. 4d).

The same-side peaks in Fig. 4 vary strongly with centrality, transitioning from nearly symmetric on $(\eta_\Delta, \phi_\Delta)$ for peripheral collisions to dramatically broadened along $\eta_\Delta$ for the more central collisions. It is important to point out that because autocorrelations are used, multiple semi-hard scattering processes per event are integrated into the single correlation peak near $\eta_\Delta = \phi_\Delta = 0$. The small excess in (0,0) bins is due to conversion-electron pairs. SSC pair cuts reduce the bins nearest (0,0) by 10% or less. Correlations from resonance ($\rho^0$, $\omega$) decays were 3% of peaks in Fig. 4 in $|\eta_\Delta| < 0.5$, $|\phi_\Delta| < 2$ [19]. Similar data for Au-Au collisions at $\sqrt{s_{NN}} = 62$ GeV where statistics are sufficient for ten centrality bins display smooth evolution...
Figure 3. Perspective views of two-particle charge independent joint autocorrelations $\bar{N}(\tilde{r}_{ij} - 1)$ on $(\eta_{\Delta}, \phi_{\Delta})$ for central (a) to peripheral (d) Au-Au collision events at 130 GeV [12]. Statistical errors are $\sim \pm 0.1$ for $|\eta_{\Delta}| = 0$ (uniform on $\phi_{\Delta}$), are nearly independent of centrality, and approximately double as $|\eta_{\Delta}|$ increases from 0 to 2 due to finite $\eta$ acceptance. Systematic errors were estimated as in [4] and are $\pm 7\%$ of signal, but increase to $\pm 8\%$ for $|\eta_{\Delta}| < 0.5$ and to $\pm 11\%$ for $|\phi_{\Delta}| < 0.05$.

Figure 4. Same data as in Fig. 3 (where $\Delta R \equiv \bar{N}(\tilde{r}_{ij} - 1)$), but $\eta_{\Delta}$-independent $\cos(\phi_{\Delta})$ and $\cos(2\phi_{\Delta})$ components (see text) have been subtracted to reveal ‘same-side’ ($|\phi_{\Delta}| < \pi/2$) structures which are assumed to be associated with semi-hard scattering processes [12].

of correlation structure from p-p–like for most-peripheral to results consistent with Fig. 3d for most-central. HIJING with jet production predicts a same-side correlation structure but no broadening with increased centrality. RQMD predictions are featureless except for some $\cos(2\phi_{\Delta})$ structure.
Joint autocorrelations in Fig. 3 (but without factor $\bar{N}$) were fitted with a model function consisting of dipole and quadrupole terms on $\phi_\Delta$, a 1D gaussian on $\eta_\Delta$ only, and a 2D same-side gaussian on $(\eta_\Delta, \phi_\Delta)$, plus constant offset:

$$F = A_{\phi_\Delta} \cos(\phi_\Delta) + A_{2\phi_\Delta} \cos(2\phi_\Delta) + A_0 e^{-\left(\frac{\eta_\Delta}{\sqrt{2}\sigma_\eta}\right)^2} + A_1 e^{-\frac{1}{2} \left\{ \left(\frac{\phi_\Delta}{\sqrt{2}\sigma_\phi}\right)^2 + \left(\frac{\eta_\Delta}{\sqrt{2}\sigma_\eta}\right)^2 \right\} + A_2. \,(3)$$

Those fit parameters confirm that with increasing centrality the 2D peak structure exhibits 1) strong and non-monotonic amplitude variation, 2) strong $\eta_\Delta$ width increase and 3) significant $\phi_\Delta$ width reduction. Same-side peak amplitudes and widths from model fits are plotted vs centrality measure $\nu$ in Fig. 5 compared to values obtained from p-p collisions. Numerical values are listed in Table 1. We speculate that the mechanism modifying the same-side peak in central Au-Au collisions is strong coupling of minimum-bias semi-hard partons (no high-$p_t$ trigger is imposed) to a longitudinally-expanding colored medium developed in more central Au-Au collisions.

6. Charge-dependent correlations on $\eta_\Delta$ versus $\phi_\Delta$

Perspective views of CD joint autocorrelations are shown in Fig. 6 using per-particle correlation quantity $\bar{N}(\bar{r} - 1)$ [13, 28]. Distributions are dominated by a 2D negative peak which is broader and elliptical for peripheral collisions (d) with major axis along $\phi_\Delta$, transitioning smoothly to a narrower and deeper peak symmetric on $(\eta_\Delta, \phi_\Delta)$ for central collisions (a). The negative peak means that unlike-charge sign pairs are more probable than like-sign pairs at small differences in pseudorapidity and azimuth. The vertical axis limits were chosen to enhance the display of the large momentum scale structure as opposed to showing the full depth of the negative peak at $\phi_\Delta = \eta_\Delta = 0$. Contributions from resonance ($\rho^0, \omega$) decays are estimated to be at most about 10% of the negative peaks in Fig. 6 in the range $|\eta_\Delta| < 0.5, |\phi_\Delta| < 2$ [19]. Results for 62 GeV Au-Au collisions show a smooth transition from p-p−like correlations to an $(\eta_\Delta, \phi_\Delta)$ symmetric negative peak for central collisions. RQMD and HIJING produce negative CD correlations but with only about 1/10 the amplitude of the data.

Distributions in Fig. 6 were fit with a five parameter model function consisting of a 2D exponential function peaked on both $\eta_\Delta$ and $\phi_\Delta$ and a 1D gaussian on $\eta_\Delta$ (the latter motivated by the p-p limiting case [23, 27]) plus constant offset, all defined relative to quantity $\bar{r} - 1$ as

$$F = B_0 + B_1 e^{-\left[ \left(\frac{\phi_\Delta}{\sqrt{2}\sigma_\phi}\right)^2 + \left(\frac{\eta_\Delta}{\sqrt{2}\sigma_\eta}\right)^2 \right]^{1/2}} + B_2 e^{-\left(\frac{\eta_\Delta}{\sqrt{5}\sigma_\eta}\right)^2}. \,(4)$$

$F$ interpolates between the 1D gaussian peak observed in p-p and the 2D exponential peak observed in central Au-Au collisions.

Charge-dependent correlations for central Au-Au collisions differ markedly from p-p data which are dominated by a 1D negative gaussian peak on $\eta_\Delta$ with $\sigma_{\eta_\Delta} \simeq 1$ [23, 27], associated with...
Longitudinal charge ordering on \( z \) (beam axis) during string fragmentation [26]. In central Au-Au collisions a large-amplitude 2D negative exponential peak dominates the correlation structure, with similar widths on \( \eta_\Delta \) and \( \phi_\Delta \), both being much reduced from that measured in p-p collisions. Variations of peak amplitudes and widths with Au-Au centrality are listed in Table 1 and shown in Fig. 7, along with p-p limiting cases (cross-hatched bands and dashed-dotted line) from STAR p-p data at 200 GeV [23] (\( \nu = 1 \)), consistent with ISR p-p data at 52.5 GeV [29]. Efficiency-corrected per-particle correlation amplitudes \( -SNB \) for central Au-Au collisions exceed those for p-p collisions by a factor 10, strongly contradicting a p-p linear superposition hypothesis [28]. These results suggest that CD correlations in Au-Au collisions, as in p-p collisions, derive from configuration-space charge ordering but that the hadronization geometry changes from 1D in p-p (i.e. parallel to beam axis) to at least two dimensions (longitudinal and azimuthal, transverse direction possible but not studied here) in central Au-Au collisions. Scattering effects could reduce the CD correlation amplitude at large \( \phi_\Delta \) but would also reduce the width on \( \eta_\Delta \) and are not expected to account for the observed symmetric peak. A hadron-opaque medium in central collisions may contribute to the newly-observed exponential peak shape where mean path length in the medium (absorption) increases monotonically with pair opening angle.

**Figure 6.** Perspective views of two-particle charge dependent joint auto-correlations \( N(\tilde{r} - 1) \) on \((\eta_\Delta, \phi_\Delta)\) for central (a) to peripheral (d) Au-Au collision events at 130 GeV [13]. Center bins at \( \phi_\Delta = \eta_\Delta = 0 \), containing photon-conversion electron pairs, were omitted from model fits. Statistical errors are approximately \( \pm 0.2 \) (one tick) for \( \eta_\Delta \sim 0 \), are independent of centrality, and approximately double as \( |\eta_\Delta| \) increases from 0 to 2 (due to finite \( \eta \) acceptance). Systematic error due to non-primary backgrounds (dominant source) [15] is estimated to be at most \( \pm 7\% \), assumed uniform for all \((\eta_\Delta, \phi_\Delta)\) in the STAR acceptance.

**Figure 7.** Left panel: Efficiency corrected amplitudes for 2D exponential (dots) and 1D gaussian (triangles) components for negative peaks in Fig. 6 [13]. Right panel: Widths \( \sigma_{\eta_\Delta} \) (dots) and \( \tan^{-1} \sigma_{\phi_\Delta} \) (triangles) [13]. Hatched regions, dash-dot line and \( \nu = 1 \) data points summarize p-p limiting values. Curves guide the eye.
Table 1. Partial list of fitting parameters and errors for models in Eqs. (2 - 4) for each centrality bin, (a) - (d) (central - peripheral). Errors (last row) represent the range of fitting errors in percent from peripheral to central. Total systematic errors for efficiency corrected amplitudes are approximately 11%, where factor $S$ [24] corrects for tracking inefficiency and background contamination. Systematic error for $S$ is 8% (listed in last row). Error for $S_{NB}$ (in brackets) is quoted as a magnitude. $\chi^2$/DoF ranges from 1 − 2 where the number of degrees of freedom (DoF) is approximately 300 for each model fit for each centrality.

| Centrality | $\bar{N}$ | $S$ | $\Delta(1/n) \times 10^4$ | $\Delta$ | $S\bar{N}A_1$ | $\sigma_{\phi_\Delta}$ | $\sigma_{\eta_\Delta}$ | $S\bar{N}B_1$ | $\sigma_{\phi_{\Delta,1}}$ | $\sigma_{\eta_{\Delta,1}}$ | $S\bar{N}B_2$ |
|------------|-----------|-----|---------------------------|--------|----------------|------------------|------------------|----------------|------------------|------------------|----------------|
| (a)        | 983       | 1.27| 0.118                     | -2.04  | 3.10           | 0.53             | 1.36             | -7.7           | 0.51             | 0.41             | -0.021          |
| (b)        | 790       | 1.25| 0.183                     | -2.53  | 3.72           | 0.54             | 1.34             | -7.7           | 0.51             | 0.41             | -0.15           |
| (c)        | 425       | 1.22| 0.611                     | -3.33  | 3.23           | 0.55             | 1.05             | -6.8           | 0.54             | 0.42             | -0.11           |
| (d)        | 116       | 1.19| 3.54                      | -8.61  | 1.93           | 0.61             | 0.58             | -4.1           | 0.66             | 0.46             | -0.51           |
| error(%)   | 8         |     | 6-24                      | 6-3    | 5-2            | 4-2              | 5-2              | 6-4            | 11-5             | 10-5             | [0.2]           |

7. Summary and conclusions

In conclusion, the dynamical origins of nonstatistical $\langle p_t \rangle$ fluctuations [4, 5] in Au-Au collisions at RHIC energies are studied via two-particle correlations on $(p_t_1, p_t_2)$ and on difference variables $\phi_\Delta$ and $\eta_\Delta$ for Au+Au collisions at $\sqrt{s_{NN}} = 62$ and 130 GeV. Initial state semi-hard parton scattering, which fluctuates from event-to-event, appears to be the source. Significant momentum dissipation to lower $p_t$ occurs resulting in local (on $\eta, \phi$) and/or event-wise temperature/velocity fluctuations and therefore significant correlation structure at lower $p_t$.

The amplitudes of those structures approximately follow binary collision scaling and far exceed that observed by similar analyses at lower energies [6, 7]. Low-$p_t$ longitudinal string-fragment correlations on $(\eta, \phi)$ subspace, prominent in p-p collisions, are quickly (with increased centrality) erased in Au-Au collisions. However, other large-amplitude correlation structures are observed including azimuth structures associated with elliptic flow and transverse momentum conservation and a same-side charge independent positive correlation peak structure which varies from a symmetric shape on $(\eta_\Delta, \phi_\Delta)$ in peripheral collisions to a highly elongated shape on $\eta_\Delta$ in central collisions. The amplitude of this same-side peak increases approximately linearly with $\nu$ but decreases for the most-central collisions at $\nu \sim 5$. Charge-dependent correlations are consistent with local charge conservation or canonical suppression of net charge fluctuations, evolving from 1D (on $\eta_\Delta$) color-string fragmentation in p-p collisions to exponentially-attenuated 2D (on $\eta_\Delta, \phi_\Delta$) charge-ordered emission from a hadron-opaque medium in central Au-Au collisions. The transition from one- to two-dimensional correlation structure occurs rapidly with increasing collision centrality. The exponential peak amplitudes increase monotonically with $\nu$ while the widths on both $\eta_\Delta$ and $\phi_\Delta$ decrease. None of these correlation structures is explained by theoretical models. These observations are consistent with a picture in which (1) semi-hard parton scattering transfers momentum $(p_t)$ to the bulk medium, inducing temperature/velocity fluctuations in the soft $p_t$ range which follow binary-collision, per-participant scaling, (2) particles correlated with semi-hard scattered partons in the early stages of the collision are carried by the longitudinally expanding medium, and (3) soft particle hadronization quickly (with increased centrality) loses ‘memory’ of the collision axis and occurs from a 2+ dimensional pre-hadronic medium.

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