Title
Hadronization geometry and charge-dependent two-particle correlation on momentum subspace (eta, phi) in Au-Au collisions at sqrt(sNN) = 130 GeV

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Hadronization geometry and charge-dependent two-particle correlations on momentum subspace ($\eta, \phi$) in Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV

We present the first measurements of charge-dependent two-particle correlations on momentum-space difference variables $\eta_1 - \eta_2$ (pseudorapidity) and $\phi_1 - \phi_2$ (azimuth) for primary charged hadrons with transverse momentum $0.15 \leq p_t \leq 2 \text{ GeV}/c$ and $|\eta| \leq 1.3$ from Au-Au collisions at $\sqrt{s_{NN}} = 130 \text{ GeV}$. We observe correlation structures not predicted by theory but consistent with evolution of hadron emission geometry with increasing centrality from one-dimensional fragmentation of color strings to higher-dimensional fragmentation of a hadron-opaque bulk medium.

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The analysis of correlations and fluctuations plays an important role in studies of the colored medium produced in ultrarelativistic heavy ion collisions [1, 2, 3]. Specifically, in-medium modification of color-string frag-
mentation and hard parton scattering in heavy ion collisions affects large-momentum-scale two-particle correlations (momentum difference comparable to the STAR detector acceptance). Large-scale correlations may result from initial-state multiple scattering 3, 6, in-medium dissipation 8 and fragmentation of the colored medium to final-state hadrons (fragmentation of strings in p-p, fragmentation of the bulk medium in A-A). String fragmentation models 8 describe correlations on \( (\eta, \phi) \) in high-energy p-p collisions in terms of local conservation of transverse momentum and net charge (canonical suppression of net-momentum and net-charge fluctuations). The corresponding process in A-A collisions is an open question. Predictions have been made of dramatic suppression of net-charge fluctuations in central A-A collisions as signaling quark-gluon plasma formation 8.

In this Letter we report the first measurement in heavy ion collisions of the centrality dependence of two-particle charge-dependent correlations (like – unlike sign charge-pairs) distributed on difference variables \( \eta_\Delta \equiv \eta_1 - \eta_2 \) and \( \eta_\Delta \equiv \eta_1 - \eta_2 \). The data suggest that local charge conservation at hadronization plus increasing system density and spatial extent result in evolution with Au-Au centralities (multiplicities differ by \( \pm 50 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities differ by \( \pm 15 \)) and primary-fragmentation (multiplicities dif-
lations are uniform on \( \eta \), with approximately double as \( |\eta| \) increases from 0 to 2 (finite \( \eta \) acceptance). Statistical errors at \( \eta \sim 0 \) vary from \( \pm 0.00015 \) for central collisions to \( \pm 0.0007 \) for peripheral collisions, again reflecting the \( 1/N \) dilution factor. In contrast, statistical errors for \( \hat{N}(r-1) \) in Fig. 2 (\( \pm 0.2 = \) one tick, for \( \eta \sim 0 \)) are independent of centrality. Statistical errors for projections in Fig. 3 are shown explicitly in that figure by error bars. Systematic errors were estimated as in [11]. The dominant systematic error is correlations from resonance \((\rho^0, \omega)\) decays, estimated to be about 10% of the peaks in Fig. 2 in the range \( |\eta| < 0.5, |\phi| < 2 \).

Joint autocorrelations in Fig. 2 were fitted with a model function consisting of a 2D function peaked on both \( \eta \) and \( \phi \) and a 1D gaussian on \( \eta \) (the latter motivated by the p-p limiting case [17, 20] plus constant offset, all defined relative to quantity \( r - 1 \) as

\[
F = A_0 + \sum_{k=1}^{2} A_k \exp\left[-\left(\frac{\eta - \eta_k}{\sigma_{\eta_k}}\right)^2 + \left(\frac{\phi - \phi_k}{\sigma_{\phi_k}}\right)^2\right],
\]

where \( k = 1 \) corresponds to the 2D peak on \( (\eta, \phi) \), and \( k = 2 \) corresponds to the independent gaussian peak on \( \eta \) \( (\sigma_{\phi_k} \to \infty) \). \( P_1 = 1 \) represents the observed exponential shape of the 2D peak, while \( P_2 \) and \( \sigma_{\eta_k} \) were fixed at 2 and 1.5 (parameter \( P \) controls peak shape). \( F \) interpolates between the 1D gaussian peak observed in p-p and the 2D exponential peak observed in central Au-Au collisions. Best-fit values for the varied parameters and \( \chi^2/\text{DoF} \) for the four centralities are listed in Table I. Total systematic error for extrapolated quantities [21] in Table I was 11% (errors added in quadrature).
The model fits indicate that with increasing centrality the 2D peak exhibits 1) strong amplitude increase, 2) significant width reduction and 3) approach to approximately equal widths on $\phi_\Delta$ and $\eta_\Delta$ for central collisions.

Charge-dependent correlations for central Au-Au collisions differ markedly from p-p data. CD correlations for p-p collisions are dominated by a 1D negative gaussian peak on $\eta_\Delta$ with $\sigma_{\eta_\Delta} \approx 1$ [17, 24], associated with charge ordering on $z$ during string fragmentation [2]. For the most peripheral Au-Au centrality in this analysis (d) we observe CD correlation structure intermediate between p-p and central Au-Au collisions. In the latter case a large-amplitude 2D negative exponential peak dominates the correlation structure, with similar widths on $\eta_\Delta$ and $\phi_\Delta$ much reduced from p-p collisions. Variation of peak amplitudes and widths with Au-Au centrality are shown in Fig. 4 along with p-p limiting cases (bands and line) from STAR p-p data at 200 GeV [20] ($\nu = 1$), consistent with ISR p-p data at 52.5 GeV [17]. Efficiency-corrected per-particle amplitudes $-SNA$ for central Au-Au collisions exceed those for p-p collisions by a factor 10, strongly contradicting a p-p linear superposition hypothesis [18].

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 to 2+ dimensions in central Au-Au collisions, contributing to the peak symmetry on $(\eta_\Delta, \phi_\Delta)$. In Fig. 4(c) the contribution from 1D charge ordering (gaussian peak on $\eta_\Delta$) is already substantially reduced for centrality (d) ($\nu \sim 2.5$) in favor of the symmetric component. A hadron-opaque medium in central collisions may contribute to the newly-observed exponential peak shape. An exponential distribution on pair opening angle (radius on $(\eta, \phi)$) is consistent with: 1) correlations detected only if both members of a correlated pair are not significantly scattered, 2) scattering probability measured by a mean free path, 3) mean path length in the medium increasing monotonically with pair opening angle. That picture assumes that CD correlations are not due to parton fragmentation outside the medium.

Contributions from charge ordering in jet fragmentation were sought by splitting central Au-Au data at $p_t = 0.5$ GeV/$c$, below which jet fragments should be negligible. Peak structures as in Fig. 2 dominated both subsamples, although the amplitudes were somewhat different.

HIJING [3] and RQMD [4] charge-dependent correlations qualitatively disagree with data. Hijing charge-dependent correlations are derived from the Lund model via Pythia, and are consequently consistent with p-p 1D string fragmentation for all A-A centralities: a 1D gaussian on $\eta_\Delta$ with amplitude about 10% of the peak in Fig. 2(a). RQMD, dominated by resonance decays and hadronic rescattering, exhibits a broad 2D gaussian on $(\eta_\Delta, \phi_\Delta)$, with amplitude also about 10% of data for central collisions. Large-scale correlations as in Fig. 4 observed for US and LS pairs in data are consistent with local charge ordering but inconsistent with CD correlations from decays of hadronic resonances such as the $\rho^0$, which would affect only the US pair type, further arguing against a resonance-gas scenario.

In summary, we have measured charge-dependent joint autocorrelations on difference variables $\phi_\Delta$ and $\eta_\Delta$ for Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV. The data are consistent with local charge conservation or canonical suppression of net charge fluctuations, evolving from 1D color-string fragmentation in p-p collisions to exponentially-attenuated 2D charge-ordered emission from a hadron-opaque medium in central Au-Au collisions. These results are qualitatively inconsistent with standard collision models. Charge-dependent autocorrelations provide unique access to the geometry of hadronization and rescattering as the energy density and spatial extent of A-A collisions increase with centrality.

We thank the RHIC Operations Group and RCF at BNL, and the NERSC Center at LBNL for their support. This work was supported in part by the HENP Divisions of the Office of Science of the U.S. DOE; the U.S. NSF; the BMBF of Germany; IN2P3, RA, RPL, and EMN of France; EPSRC of the United Kingdom; ST AR p-p data at 200 GeV [20] (Fig. 4, along with p-p limiting cases (bands and line) from STAR p-p data at 200 GeV [20] ($\nu = 1$), consistent with ISR p-p data at 52.5 GeV [17]. Efficiency-corrected per-particle amplitudes $-SNA$ for central Au-Au collisions exceed those for p-p collisions by a factor 10, strongly contradicting a p-p linear superposition hypothesis [18].

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[10] An autocorrelation is a projection by averaging of a distribution on \((x_1, x_2)\) onto difference variable \(x_1 - x_2\).
[15] Centrality classes d) - a) respectively were defined by \(N/N_0\) cuts at \(> 0.03, 0.21, 0.56\) and \(> 0.79\).
[16] Quantity \(\nu \simeq 5.5 (N_{part}/N_{part,max})^{1/3} \simeq 5.5 (N/N_0)^{1/3}\) estimates mean participant path length as a number of encountered nucleons. \(N_0\) is the half-maximum end point of the minimum-bias distribution plotted as \(d\sigma/dN_{ch}^{1/4}\).
[18] \(N(t-1)\), measuring per-particle correlations (typically \(O(1)\) for all centralities), is invariant with centrality if A-A collisions are linear superpositions of p-p collisions.
[21] Extrapolation factors \(S\) for \(\bar{N}A_k\) provide corrections for background contamination and tracking inefficiency. Systematic error in \(S\) was estimated to be \(\pm 8\%\).