Implications of hadronization as a rapid traversal of the QCD phase boundary are explored for correlation structures in jets, N-N collisions and heavy-ion collisions. Hadronization viewed as a partition of the prehadronic system restricts the scale interval over which power-law jet correlation structures survive. Rapid traversal of the QCD phase boundary may result in a lattice-like residual structure in N-N and A-A configuration space accessible to momentum-space correlation analysis via Hubble flow.

1 Introduction

The study of pQCD correlation structure in jets at LEP and HERA considers the LPHD hypothesis and the effects of hadronization on expected pQCD gluon bremsstrahlung correlations. Closely-related issues emerge in the treatment of correlations and fluctuations in heavy-ion collisions at the SPS and RHIC and charge-dependent correlations previously observed in the axial phase space of N-N collisions.

A recent Delphi factorial-moment jet correlation analysis indicates disagreement with the LPHD hypothesis, possibly due to hadronization. I consider the hadronization process as a rapid traversal of the QCD phase boundary and examine the consequences for correlations and fluctuations. I introduce a generalized treatment of transverse flow effects in nuclear collisions and describe newly observed large-scale momentum correlation structures which hint at a regular fm-scale space structure in heavy-ion collisions.

2 Jet Correlations

Jet correlation studies may be applied to gluon bremsstrahlung correlations. The tree-like bremsstrahlung should produce characteristic power-law behavior (intermittency) in correlation measures such as the normalized factorial moments. Analysis results depend strongly on the dimensionality of the analysis space. Projections to lower dimension tend to reduce correlation effects. In a 1D Delphi intermittency analysis, one observes little evidence for extended bremsstrahlung structure. The result can be interpreted as indicating
large-scale jet width fluctuations.

The hadronization process acts to restrict the scale interval over which the double log approximation (DLA) and local parton-hadron duality hypothesis (LPHD) are valid. The LPHD hypothesis implies point-to-point transfer of correlation structure from parton to hadron system, whereas the Delphi result suggest a sharp scale restriction – correlation transfer over a restricted scale interval – implying that hadrons act as partition elements: small-scale glue structure is reabsorbed into finite-size hadrons. The hadronization process is not a point-coalescence process but instead has finite spatial extent. I now consider hadronization as rapid traversal of the QCD phase boundary.

3 Rapid Traversal of the QCD Phase Boundary

In Fig. 1 an idealized phase boundary separates regions with different densities of DoF (left panel). At the boundary large-scale correlations may cause increased critical fluctuations. Depending on the speed of traversal a dynamical system may ‘remember’ more or less about the two boundary aspects: DoF density difference and critical correlations. Fluctuation amplitudes are illustrated in the right panel. We ask whether a system ‘remembers’ a prehadronic correlation state after sudden traversal. Increased and decreased variance depend on traversal rate and observation scale. Suppression of hadronic fluctuations (e.g., momentum, flavor, charge, baryon number) implies an anticorrelated distribution. Such a distribution must approximate a lattice in configuration space. Rapid traversal of the QCD phase-boundary should be indicated by a local lattice structure in the distribution of final-state hadrons. Suppressed isovector fluctuations (fluctuations in net pion charge) may reflect a chirally symmetric precursor system, and approach to an isospin antiferromagnet: two pion charge species form individual like-sign distributions approximating lattices juxtaposed to provide unlike-sign nearest neighbors. This picture is supported by the correlation systematics for

![Figure 1. Distribution of kinetic degrees of freedom (left) and relative variance (right) on a parameterized thermodynamic state space. Critical correlations formed at the phase boundary may result in reduced DoF density and corresponding increased critical fluctuations.](image-url)
charged hadrons observed in N-N data.

4 Phase-space Correlations in N-N and A-A Collisions

N-N axial phase space contains very strong $x$-$p$ correlations due to axial Hubble flow (Bjorken expansion) shown in the left panel of Fig. 2. Correlations in configuration space ($z$) are observable directly in momentum space ($Y$), giving direct access to small-scale configuration-space structure. Correlation structures are observed in the two-particle momentum density $\rho_2(y_1, y_2)$ plotted on rapidity difference and azimuth-angle difference. Correlations in N-N collisions indicate substantial anticorrelation of like-sign hadrons and correlation of unlike-sign hadrons at small length scale, consistent with formation of a 1D lattice structure during hadronization.

A central issue for HI collisions is the correlation structure of transverse phase space. Do initial-state strings cross couple, are color and other measures transversely deconfined? Evidence for small-scale (anti)correlation or lattice structure in HI collisions would be most significant if observed in the transverse phase space. We require a means to probe directly the local structure of hadronic space correlations.

Fig. 2 contrasts autocorrelation densities for N-N axial phase space and HI transverse phase space at freezeout. Whereas the N-N case shows a large $x$-$p$ correlation due to superthermal Hubble flow the autocorrelation density on heavy-ion transverse phase space shows only a small correlation due to subthermal Hubble flow. Despite the weak correlation in the heavy-ion case configuration-space correlations may still be observed in momentum space. I now generalize the relationship between collective flow and two-particle momentum correlations.
5 Two-particle Correlations and Hubble Flow

To extend the description of transverse flow effects we assume that pair emission is not random but instead depends locally on partner separation distance. Guided by FSI treatments we factor the two-particle emission density \( g(x_1, x_2, p_1, p_2) \) into dependence on mean pair position \( x \) and on partner separation \( y \). The Wigner density is then

\[
S_2(x_1, x_2, p_1, p_2) \approx g_+ (x, k) g_- (y, q) f_1(x_1, p_1) f_1(x_2, p_2).
\]

We represent the two-point momentum distribution \( P_2(p_1, p_2) \) as a sum of two terms \( A(k, q) + B(k, q) \), where \( B(k, q) \) contains the usual HBT Fourier transform of no further interest to us here. \( A(k, q) \) is conventionally assumed to be the product of two single-particle distributions.

We approximate radial flow locally by analogy with cosmological Hubble flow and assume the form \( \nabla \beta = H \mathcal{I} \) from which \( \Delta \beta(x) \approx H \Delta x \). We assume a Cooper-Frye form for the flow-dependent momentum density. Integrating the Wigner density we obtain the non-interference term of the two-particle momentum distribution as the product of three factors

\[
A(k, q) \approx m_{t1} m_{t2} e^{-\frac{m_{t1}+m_{t2}}{T}} \cdot \int d^4 x g_+ (x, k) \exp \left( \frac{2H}{T} k \cdot x \right) \cdot \int d^4 y g_- (y, q) \cosh \left( \frac{H}{2T} q \cdot y \right),
\]

where \( x = (x_1 + x_2)/2 \), \( y = y_1 - y_2 \), are mean and relative four-positions, \( k = (p_1 + p_2)/2 \), \( q = p_1 - p_2 \) are mean and relative four-momenta, \( H \) is the local transverse-flow Hubble constant and \( T \) is the local temperature.
momentum $k_t$. The third factor represents a newly-identified quadratic dependence on momentum difference $q$ resulting from transverse Hubble flow. The blue shift and quadratic dependence are represented respectively in the left and right panels of Fig. 3. The third factor contributes a positive or negative quadratic offset to the two-particle correlator $C_2(k, q)$ on pair-momentum difference if both Hubble flow and sibling/mixed-pair space-time separation differences are present.

6 Two-particle $p_t$ Distributions

Two-particle $p_t$ distributions for Pb-Pb collisions at \( \sqrt{s_{NN}} = 17 \) GeV (NA49) in Fig. 4 show significant structure in the pair density ratio. The large-scale quadratic structures (represented by parameterized fits in the right panels) are not related to quantum correlations or tracking effects. Like-sign pairs (top) exhibit an anticorrelated (concave up) distribution on momentum difference, whereas unlike-sign pairs (bottom) exhibit a correlated (concave down) distribution. Referring to Eq. (2) we see that these results indicate anticorrelation of like-sign pairs and correlation of unlike-sign pairs in transverse configuration space – formation of a lattice structure – an isospin antiferromagnet. We have tested this interpretation with a MC simulation using a transverse lattice to model a boost-invariant system. Transverse momenta from the measured NA49 $p_t$ spectrum were randomly assigned to particles. A radial flow field also consistent with NA49 measurement was superimposed giving good qualitative agreement with the experimental results.
7 Conclusions

Hadronization modeled as rapid traversal of the QCD phase boundary implies related correlation effects in jets, N-N axial phase space and A-A axial and transverse phase space. Formation of a transverse lattice structure at the $fm$ length scale in high-energy heavy-ion collisions should be possible based on observations of a 1D axial lattice structure in N-N collisions provided there is rapid hadronization from a prehadronic state. A recent two-particle correlation analysis in the transverse phase space of Pb-Pb collisions at the SPS has revealed isospin-dependent correlation structures which suggest that a combination of transverse Hubble flow and $fm$-scale space lattice structure produces observed large-scale momentum correlations.

Scale-dependent jet correlation studies combined with small-scale probes of the N-N and heavy-ion hadronic freezeout surface via Hubble flow and precision analysis techniques provides new access to the small-scale structure of the chemical freezeout surface and the QCD phase boundary. We search for definitive evidence in HI collisions for a deconfined 3D partonic system. Evidence for a pion lattice in transverse phase space may offer conclusive evidence for a locally-equilibrated prehadronic state in HI collisions.

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