COLLECTIVE EFFECTS IN A MEDIUM AND A MODEL OF COMPOUND FLOW IN RELATIVISTIC HEAVY ION COLLISIONS

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A new analytical approach is presented for analysis of two-particle azimuthal correlations in heavy ion collisions at relativistic energies. This approach suggests that elliptic flow measured by experiment has a compound structure, namely, that it may come from superposition of several components. General expressions have been derived for the two-particle correlation function isolating the contribution due to anisotropic flow. The model of compound flow takes into account the number of jets per event, average multiplicity per jet, dependence of jet yield on the orientation with respect to the reaction plane, and independent "soft" particle production. These analytic calculations provide the framework for a consistent description of the elliptic flow measured via the single-particle distribution with respect to the reaction plane, jet yield per event, and the amplitude of flow-like modulation in the two-particle distribution in the relative azimuthal angle.

Keywords: azimuthal correlations; flow; heavy ion.

1. Introduction

The specific fundamental prediction of QCD most often highlighted in the discussions of experimental program at RHIC (BNL) and LHC (CERN) is that at high energy densities an ordinary hadronic matter undergoes a phase transition to a new state of hot and dense strongly interacting matter, the QGP, and reproduce the early Universe conditions. A study of collective behavior in heavy-ion collisions provides one of the most sensitive and promising probes for investigation of possible QGP formation and elucidating its properties.

Large collective flow measured in Au-Au collisions at the RHIC provides direct evidence of strong pressure gradients in a hot and dense medium created in a collision. Quenching of di-jets observed in central Au-Au collisions at RHIC by studying the two-particle azimuthal distributions at high transverse momenta is interpreted as final state effect and as an evidence for extreme energy loss of partons propagating in the hot deconfined matter. At intermediate transverse momenta, both effects are present in the azimuthal correlations of hadron pairs and it is important to disentangle the contributions of flow and jet components.

Thus azimuthal correlations of hadron pairs provide one of the primary tools for the experimental investigation of collective flow phenomena and identifying the products of hard jets. A new analytical approach is presented for analysis of two-particle azimuthal correlations in heavy ion collisions at relativistic energies.

2. Two-particle correlations: disentangling flow and jets

In the following, we suggest a general framework for analysis of the azimuthal correlations of hadron pairs in heavy-ion experiments at high (RHIC and LHC) energies. Two-particle distributions in the relative azimuthal angle of charged high $p_T$ particles measured in p+p, d+Au, and Au+Au collisions at RHIC exhibit a jet-like correlation characterized by the peaks at $\Delta\phi = 0$ (near-side jets) and at $\Delta\phi = \pi$ (opposite-
side jets). In Au+Au collisions, the particle correlations due to elliptic flow also contribute, resulting in a cosine-like pattern. We suggest that elliptic flow measured by experiment has a compound structure, namely, that it may come from superposition of several components. We derive general expressions for the two-particle correlation function isolating the contribution due to anisotropic flow. We take into account the number of jets per event, average multiplicity per jet, dependence of jet yield on the orientation with respect to the reaction plane, and independent "soft" particle production. The different distributions are normalized by standard way, namely, all single-particle distributions are normalized on total number of particles per event, average multiplicity per jet, and all type two-particle distributions are normalized by standard "soft" particle production. The difference of jet yield on the orientation with respect to the reaction plane, and independence of jet yield on the orientation with respect to the reaction plane: 

\[ 2\pi \frac{dn}{d\phi} = N_s [1 + 2v_2 \cos 2\phi], \]

where \( N_s \) is the number of "soft" particles, or particles which have no other azimuthal correlations besides those due to elliptic flow. Elliptic flow also generates azimuthal anisotropy in the angle difference \( \Delta \phi \) of "soft" particle pairs:

\[ 2\pi \frac{d^n_{1,2}}{d(\Delta \phi)} = N_s \left[ (1 + 2v_2^2) \cos 2\Delta \phi \right], \tag{1} \]

where \( N_s = N_s (N_s - 1) \) is the number of "soft" particle pairs. Suppose that for events where hard scattering took place, the \( N_h \) "hard" particles were produced via fragmentation of high energy partons. These particles may also be correlated with the impact parameter due to parton energy loss and the azimuthal dependence of the path length, but in general case their degree of correlation \( (v_2^h) \) will be different than that of the "soft" particles. The single-particle azimuthal distribution of "soft" and "hard" particles with respect to the reaction plane is then:

\[ 2\pi \frac{dn}{d\phi} = N [1 + 2\tilde{v}_2 \cos 2\phi], \tag{2} \]

where \( N = N_s + N_h \) – total multiplicity of particle satisfied some cuts per event. Thus, experiments measure the "effective" \( \tilde{v}_2 = (N_s v_2^s + N_h v_2^h) / (N_s + N_h) \).

Hard scattered partons fragment into a high energy cluster (jet) of hadrons which are distributed in a cone of size \( \Delta \eta \Delta \phi \sim 0.7 \) in pseudorapidity and azimuth. Let the two-particle azimuthal distribution within a single jet/dijet be of some general form:

\[ 2\pi \frac{d{n_{1,2}}}{d(\Delta \phi)} = \langle n^h \rangle (\langle n^h \rangle - 1) f(\Delta \phi), \]

where \( \langle n^h \rangle \) is the average multiplicity of particles within a single jet/dijet, and \( f(\Delta \phi) \) is a function which describes the intra-jet correlations of hadron pairs within a jet cone. In elementary high-energy collisions, \( f(\Delta \phi) \) closely resembles the Gaussian distribution. In heavy-ion collisions, we are interested in measuring possible medium modifications of \( f(\Delta \phi) \). The function \( f(\Delta \phi) \) can be parameterized as following:

\[ f(\Delta \phi) = A_N \frac{1}{\sqrt{2\pi \sigma_N^2}} \exp \left( -\frac{(\Delta \phi)^2}{2\sigma_N^2} \right) + A_B \frac{1}{\sqrt{2\pi \sigma_B^2}} \exp \left( -\frac{(\Delta \phi - \pi)^2}{2\sigma_B^2} \right) + \varepsilon, \tag{3} \]

where the \( A_N, \sigma_N \) – normalization factor and width for the near-side peak \( (\Delta \phi = 0) \), \( A_B, \sigma_B \) – normalization factor and width for the opposite-side peak \( (\Delta \phi = \pi) \), and \( \varepsilon \) – (unknown) factor which is corresponds to medium modification of hadron jets. The problem of normalization of two-particle distribution doesn’t discussed in this paper in detail. Experimental distributions are normalized on number of trigger particles with
where the new parameters are

\[ C \quad \text{and} \quad \cos 2\Delta \]

Above, the coefficient \( \phi \cos 2\Delta \)

The total number of particles from jets is then given by the following equation:

\[ N_{h} = N_{h} \langle n^{b} \rangle. \]

Combining the intra-jet correlations with correlations with respect to the impact parameter, the two-particle azimuthal distribution for "hard" particles is then given by the following equation:

\[
2\pi \frac{d\eta_{1,2}}{d(\Delta \phi)} = N_{h} (N_{h}/N_{J} - 1) f(\Delta \phi) + N_{h}^{P} \left[ 1 + 2 \left( v_{2}^{h} \right)^{2} \cos 2\Delta \phi \right].
\]

where the first term describes the correlation of particles from the same jet/dijet, and the second term corresponds to the correlation of particles from different jets/dijets (pure elliptic flow of "hard" particles), \( N_{h}^{P} = N_{h}^{2} \left( 1 - 1/N_{J} \right) \) - number of "hard" particle pairs per event with the exception of pairs between "hard" particles within single jet.

Thus the combined two-particle distribution of "soft" and "hard" particles will be a superposition of the "soft" and "hard" distributions and an additional cross term with standard normalization:

\[
2\pi \frac{d\eta_{1,2}}{d(\Delta \phi)} = N_{h} (N_{h}/N_{J} - 1) f(\Delta \phi) + C \left[ 1 + 2P \cos 2\Delta \phi \right],
\]

where the new parameters are \( C = N_{s}^{P} + N_{h}^{P} + 2N_{s}N_{h}h, PC = N_{s}^{P} \left( v_{2}^{s} \right)^{2} + N_{h}^{P} \left( v_{2}^{h} \right)^{2} + 2N_{s}N_{h}v_{2}^{s}v_{2}^{h}. \)

As one can see from the expression above, the coefficient \( P \) in front of \( \cos 2\Delta \phi \) depends on five parameters, namely \( N_{J}, N_{s}, N_{h}, v_{2}^{s}, \) and \( v_{2}^{h} \) in non-trivial way.

This coefficient is the square of "generalized" flow in the framework of this model of two-component flow. The total multiplicity \( (N_{s} + N_{h}) \) is measured experimentally. Experiments also measure \( v_{2} = (N_{s}v_{2}^{s} + N_{h}v_{2}^{h})/(N_{s} + N_{h}). \) More information can be extracted from the experimental data using conditional two-particle azimuthal correlations for which one of the particles is detected under fixed directions with respect to the reaction plane.

We also investigate how the two-particle azimuthal distributions change when the orientation of one of the particles is restricted to a region in-plane or out-of-plane with respect to the reaction plane. The analytic calculations below provide the framework for a consistent description of the elliptic flow measured via the single-particle distribution with respect to the reaction plane, jet yield per event, and the amplitude of flow-like modulation in the two-particle distribution in the relative azimuthal angle. Let the trigger particle be confined in the transverse plane to the \(-\pi/4 < \phi < \pi/4\) ("in-plane"), and \(\pi/4 < \phi < 3\pi/4\) ("out-of-plane"), respectively. Below we consider the simplest ideal case, namely, the case of known reaction plane. The number of in/out "soft" and "hard" particles is:

\[
(N_{\text{out}}^{\text{in}})_{s} = \frac{N_{s}}{2\pi} \left( \pi \pm 4v_{2}^{s} \right),
\]

\[
(N_{\text{out}}^{\text{in}})_{h} = \frac{N_{h}}{2\pi} \left( \pi \pm 4v_{2}^{h} \right).
\]

There are four terms to the total number of possible pairs for the combined "soft+hard" in/out-plane two-particle distribution:

\[
2\pi \left( \frac{d\eta_{1,2}}{d(\Delta \phi)} \right) = \text{soft}^{\text{in}} + \text{soft}^{\text{out}} \cdot \text{soft} + \text{hard}^{\text{in}} \cdot \text{hard} + \text{hard}^{\text{out}} \cdot \text{hard}.
\]

\*that is \( N_{J} \) acts of hard parton scattering per event
By adding up all four terms and combining, we get the following general expression for two-particle "in/out-plane" distribution:

\[
2\pi \left( \frac{dn_{1,2}}{d(\Delta \phi)} \right)_{\text{out}} = (N_{\text{out}})^{\text{in}} h \left( \frac{N_h}{N_J} - 1 \right) f(\Delta \phi)
\]

\[ + C_{\text{out}}^{\text{in}} \left[ 1 + 2P_{\text{out}}^{\text{in}} \cos 2\Delta \phi \right],
\]

\[
2\pi C_{\text{out}}^{\text{in}} = C_{\text{out}}^{\text{in}} \equiv \tilde{C}_{\text{out}}^{\text{in}} = \left( \pi \pm 4v_s^2 \right) \left( N_s N_h + N_p^p \right),
\]

\[
\tilde{C}_{\text{out}}^{\text{in}} P_{\text{out}}^{\text{in}} = N_p^p v_s^2 \left( \pi v_s^2 + 2 \right) + N_h v_h^2 \left( \pi v_h^2 + 2 \right)
\]

\[ + 2N_s N_h \left( \pi v_s^2 v_h^2 + v_s^2 + v_h^2 \right). \quad (7)
\]

By performing the combined fit of Eqs.(2), (5) and (7) to the experimental data, constraining the integrals, and using the fact that flow cancels out at \( \phi, \Delta \phi = \pi/2 \), it may be possible to unambiguously determine parameters \( N_J, N_s, N_h, v_s^2, v_h^2 \) and study the medium modification of the two-particle distribution within a jet by the following way.

Thus jets are sensitive to the collective flow field in the collision region. The reason of the jet asymmetry can be both collective flow of medium (flow of "soft" particles) and flow of "hard" particles (i.e. jet correlations with respect to event plane - jet flow). Also the "hard" flow component can influences on the structure of away-side peak in hadron distribution for RHIC data. In particular the jet flow can provides some asymmetry of Max cone or ring of Cherenkov gluons.

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