Correlations in multiparticle production

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Abstract

We discuss correlations in the hadron production in the \( pp \)-collision with emphasize on the ridge-like structure origin in the two-particle correlation function. We suggest that this structure can appear due to a rotating nature of the transient state of matter generated in the intermediate stage of proton collision.

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Introduction

Nowadays the LHC is collecting data and providing experimental results at the largest world energy \( \sqrt{s} = 7 \text{ TeV} \). Along with realization of its discovery potential, the LHC experimental program renewed interest to the well known unsolved problems providing deepened insights into those issues. In this context the multiparticle production studies bring us a clue to the mechanisms of confinement and hadronization. Confinement of a color (i.e. the fact that an isolated color object has an infinite energy in the physical vacuum) is associated with collective, coherent interactions of quarks and gluons, and results in formation of the asymptotic states, which are the colorless, experimentally observable particles. The inelastic processes involve large number of particles in the final state.

On the other side, the experimental measurements often reveal high degrees of a coherence in the relevant observables. No doubt these collective effects are very important for understanding of the nonperturbative collision dynamics. Such collective effects are associated, in particular, with unitarity regulating the relative strength of elastic and inelastic processes and connecting the amplitudes of the various multiparticle production processes.

Thus, it seems to be important now to analyze recent experimental data and try to make first conclusions on the nature of a matter produced in \( pp \) collisions, i.e. is it weakly interacting or it remains to be a strongly interacting one as it was observed at RHIC in \( AA \) collisions? In the latter case one can expect that proposed in [2] mechanism related to the rotation of transient matter should be working at the LHC energies and therefore the observed at RHIC phenomena should be observed in \( pp \)-collisions also.
Ridge-like structure in the correlation function and rotation of quark-pion liquid

The ridge structure was observed first at RHIC in peripheral collisions of nuclei in the two-particle correlation function in the near-side jet production (cf. recent paper [4] and references therein). It was demonstrated that the ridge particles have a narrow $\Delta \phi$ correlation distribution (where $\phi$ is an azimuthal angle) and wide $\Delta \eta$ correlations ($\eta$ is a pseudorapidity). The ridge phenomenon was associated with the collective effects of a medium.

The similar structure in the two-particle correlation function was observed by the CMS Collaboration [5]. This is rather surprising result because the ridge structure was observed for the first time in $pp$-collisions. Those collisions are commonly treated as a kind of “elementary” ones under the heavy-ion studies and therefore often used as the reference process for detecting deconfined phase formation on the base of difference between $pp$- and $AA$-collisions. It is evident now that such approach should be revised in view of this new and unexpected experimental result. This ridge structure has been observed in the small number of events in the definite kinematical region. In addition, those events have certain limitations on their multiplicity. Despite those facts this discovery can be compared with discovery of power-like dependence on transverse momenta of the inclusive cross-sections which demonstrated a presence of the hard interactions (and has also been seen in the comparatively small number of events).

The particle production mechanism proposed in the model [2] takes into account the geometry of the overlap region and dynamical properties of the transient state in hadron interaction. This picture assumes deconfinement at the initial stage of interaction. The transient state appears as a rotating medium of massive quarks and pions which hadronize and form multiparticle final state. Essential point for this rotation is the non-zero impact parameter.

Indeed, the inelastic overlap function $h_{\text{inel}}(s,b)$,

$$h_{\text{inel}}(s,b) \equiv \frac{1}{4\pi} \frac{d\sigma_{\text{inel}}}{db^2},$$

has a peripheral impact parameter dependence at the energy $\sqrt{s} = 7$ TeV due to the reflective scattering [3]. Note, that unitarity equation rewritten at high energies for the elastic amplitude $f(s,b)$ has the form

$$\text{Im} f(s,b) = h_{\text{el}}(s,b) + h_{\text{inel}}(s,b)$$

and $h_{\text{inel}}(s,b)$ is the sum of all inelastic channel contributions. Due to this peripherality, the mean multiplicity

$$\langle n \rangle(s) = \frac{\int_0^\infty bdb(n)(s,b)h_{\text{inel}}(s,b)}{\int_0^\infty bdbh_{\text{inel}}(s,b)}$$

gets the main contribution from the collisions with non-zero impact parameters. Thus, one can assume that the events with high multiplicity at the LHC energy $\sqrt{s} = 7$ TeV correspond to the peripheral hadron collisions [3]. Thus, at the LHC energy $\sqrt{s} = 7$ TeV there is a dynamical selection of peripheral region in impact parameter space responsible for the inelastic processes. In the nuclear reactions such selection is provided by the relevant experimental adjustments. Note, that the ridge-like structure in the nuclear reactions has also been observed in peripheral collisions only [4].
The geometrical picture of hadron collision at non-zero impact parameters implies that the generated massive virtual quarks in overlap region could obtain very large initial orbital angular momentum at high energies. Due to strong interaction between quarks this orbital angular momentum leads to the coherent rotation of the quark system located in the overlap region as a whole in the $xz$-plane (Fig. 1). This rotation is similar to the liquid rotation where strong correlations between particles momenta exist. Thus, the orbital angular momentum should be realized as a coherent rotation of the quark-pion liquid as a whole. The assumed particle production mechanism at moderate transverse momenta is an excitation of a part of the rotating transient state of massive constituent quarks (interacting by pion exchanges). Due to the fact that the transient matter is strongly interacting, the excited parts should be located closely to the periphery of the rotating transient state otherwise absorption would not allow to quarks and pions leave the interaction region (quenching).

The mechanism is sensitive to the particular direction of rotation and to the rotation plane orientation. This will lead to the narrow distribution of the two-particle correlations in $\Delta \phi$. However, two-particle correlation could have broad distribution in polar angle ($\Delta \eta$) in the above mechanism (cf. Fig. 1). Quarks in the exited part of the cloud could have different values of the two components of the momentum (with its third component lying in the rotation $xz$-plane) since the exited region $V_R$ has significant extension.

Thus, the ridge-like structure observed in the high multiplicity events by the CMS Collaboration can be an experimental manifestation of the coherent rotation of the transient matter in hadron collisions. The narrowness of the two-particle correlation distribution in the asimuthal angle is the distinctive feature of this mechanism.

There should be other experimentally observed effects of this collective effect, one of them is the directed flow $v_1$ in hadron reactions, with fixed impact parameter discussed in [2]. Rotation of transient matter will affect also elliptic flow $v_2$ and average transverse momentum of secondary particles produced in proton-proton collisions [6] [7]. Due to rotation, in particular, the following relation of the average transverse momentum with the mean multiplicity of secondaries

$$\langle p_T \rangle (s) = a + b \langle n \rangle (s)$$

takes place. This relation is in a good agreement with existing experimental data [6].
The above discussion shows that the nature of the state of matter revealed at the LHC in proton collisions is the same as the nature of the state revealed at RHIC in nuclei collisions. The details and discussions of the other collective effects such as elliptic flow can be found in [8].

Conclusion

To conclude we would like to note that the vanishing anisotropic flows and appearance (simultaneous) of the secondary particles polarization (cf. [8]) are the signals of the genuine QGP formation in the mechanism based on the rotating behaviour of the transient state. The leading role belongs to orbital angular momentum in the above phase transition.

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