Charge balance functions and the transverse flow

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Abstract Correlations between opposite charge particles emitted in ultrarelativistic heavy-ion collisions can be used as a measure of the transverse flow present at the time of the decoupling of the charged pair. The width of the charge balance function in azimuthal angle depends on the transverse velocity and the temperature of the emitting source. Asymmetry in the balance function between in plane and out of plane emission can serve as a probe of the azimuthal asymmetry of the velocity field in the source.

Key words ultrarelativistic heavy-ion collisions • particle correlations • collective flow

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Charged particles are produced in pairs of opposite electric charge, baryon number or strangeness, due to the obvious constraint of charge conservation in microscopic processes. The effect of this constraint is small for total multiplicities of particles produced in heavy-ion collisions. Nevertheless, the correlations between charged particles due to the local charge conservation can be revealed by the charge balance function [8]. The charge balance function in rapidity $B(\delta y)$ shows how many opposite charge particles are observed at a relative distance δy in rapidity. Due to the strong longitudinal flow, the distance between charges in rapidity is frozen at the time of the creation of the pair [3]. This led to the idea that a small width of the balance function in rapidity, smaller than about one unit of rapidity distance observed between charges produced in elementary collisions, would signal a late creation of charges. A mechanism of a such late creation of charges could be the hadronization from a thermalized quark-gluon plasma. Experimental results indicate that such a late charge creation scenario is indeed realised. However, it could be understood not only as a late charge creation due to the hadronization, but also as the creation of charged pairs late at the thermal freeze-out in a hadron gas [5, 7]. Charge balance functions represent the picture of particle correlations at the freeze-out. Particle emission from a thermal source must obey the charge conservation locally. In a thermal hadron gas model charged pairs come from two sources. The first one is the emission of particle pairs from a local thermal source. The local thermal source itself can be characterised by the transverse velocity and the temperature. The second source of correlated unlike charged particles (pions) is the decay of neutral

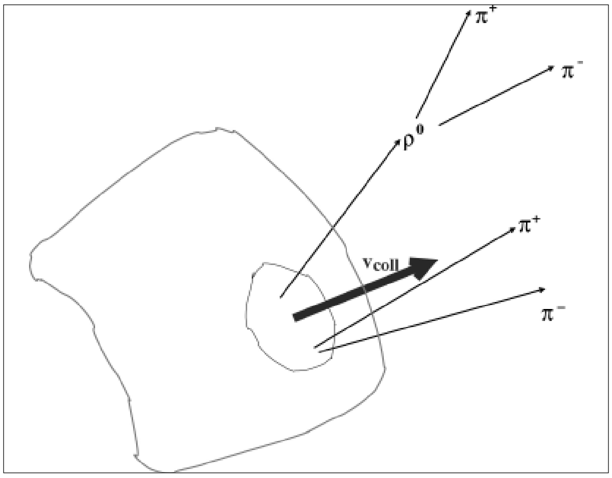

Fig. 1. Emission of pion pairs from a thermal source moving with velocity V_{coll}. Pions come from the decays of neutral resonances or are emitted in pairs directly from a local element of the freeze-out surface.

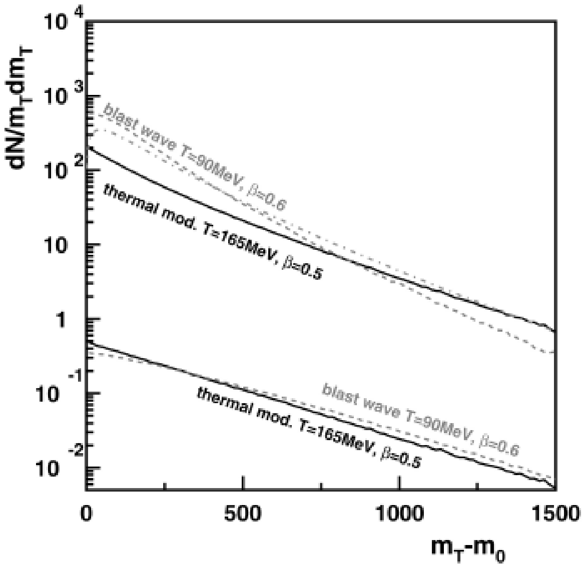

Fig. 2. Spectra of pions (upper curves) and protons (lower curves) emitted from thermal sources with two different set of parameters, high temperature and moderate transverse flow (solid lines) and small temperature and large transverse flow (dashed lines). The dashed-dotted line represents pion spectra from a high temperature source including pions coming from the decay of resonances. The normalisation is arbitrary.

resonances (Fig. 1). The scenario of particle pair emission from a local source at the freeze-out describes reasonably the experimental data on the charge balance function in rapidity [5, 7]. Some sensitivity of the width of the charge balance function $B(\delta y)$ to the amount of the transverse flow is observed in model calculations and can explain the decrease of the width with the centrality of the collision. Transverse momentum correlations have also been discussed as a measure of the transverse flow profile [10].

In this paper we show that the charge balance function in the relative azimuthal angle between two particles carrying opposite charges is a very sensitive probe of the conditions at the freeze-out. The charge balance function in azimuthal angle is defined as

$$B(\delta\varphi,\varphi)=\frac{1}{2}\left[\frac{N_{+-}(\delta\varphi,\varphi)-N_{++}(\delta\varphi,\varphi)}{N_{+}(\varphi)}\right. \\ \left.+\left[\frac{N_{-+}(\delta\varphi,\varphi)-N_{--}(\delta\varphi,\varphi)}{N_{-}(\varphi)}\right]\right] \tag{1}$$

where: $N_{+-}(\delta\varphi,\varphi)$ is the number of pairs where a positive charge particle is emitted at the angle φ and a negative charge particle at the angle $\varphi + \delta\varphi$; $N_{+}(\varphi)$ is the number of positive charge particles emitted at the angle φ; other symbols are defined analogously. For the analysis of the average flow we use $B(\delta\varphi)$ depending only on the relative angle of the pair, defined as the sum over the angle φ of the balance function $B(\delta\varphi,\varphi)$.

Thermal emission of hadrons and resonances supplemented with a cascade of decays of unstable particles can describe the spectra of particles emitted in heavy-ion collisions. Transverse momentum spectra are determined by the temperature and the transverse flow. There is a large degree of uncertainty in the determination of these parameters of the freeze-out from the spectra alone. The same experimental spectra can be fitted using different sets of parameters. In Fig. 2 are shown the results for two extreme assumptions about the freeze-out. The first one is the single freeze-out model [6], where the kinetic freeze-out occurs at the same time as the chemical one. The temperature of the chemical freeze-out is fixed from a fit to particle ratios at a relatively high value of 165 MeV for the RHIC data. The transverse flow is generated from a Hubble expansion, and the average transverse velocity at the freeze-out is $0.5c$. A different model of the time development in the collision lies at the basis of the blast wave parameterisation. The kinetic freeze-out takes place significantly after the chemical one. The temperature at the second freeze-out is independent and, as it turns out from the fits, is much lower than the chemical one. The transverse flow and the temperature at the chemical freeze-out are both extracted from a fit to the transverse momentum spectra of pions, kaons and protons. The temperature and the transverse flow depend on the centrality of the event, in the following we use the temperature and the transverse flow profile fitted to central collisions at the highest RHIC energy, with $T = 90$ MeV and the average flow velocity $0.6c$ [2]. The combined effects of the transverse flow, freeze-out temperature and resonance decays make the extraction of the freeze-out parameters from the observed spectra inconclusive. Also the HBT radii can be approximately reproduced using the two different parameterisations.

In the single freeze-out model, particles are created at the chemical freeze-out and stop interacting immediately. Therefore, their momentum distribution reflects the momenta of particles at the time of the creation of the charges. Balance functions are a measure of the momenta of particles at that moment. If the kinetic freeze-out is delayed with respect to the chemical one, the momenta of the particles are changed on their way from the creation point to the detector. However, one can assume that the two correlated opposite charge

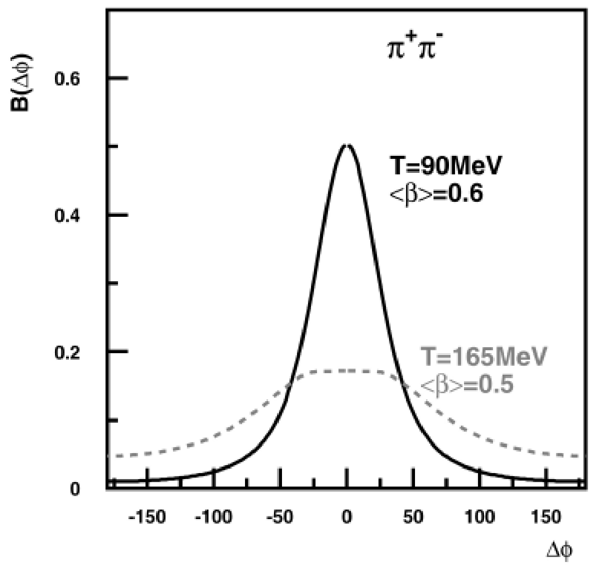

Fig. 3. The charge balance function in azimuthal angle for pions.

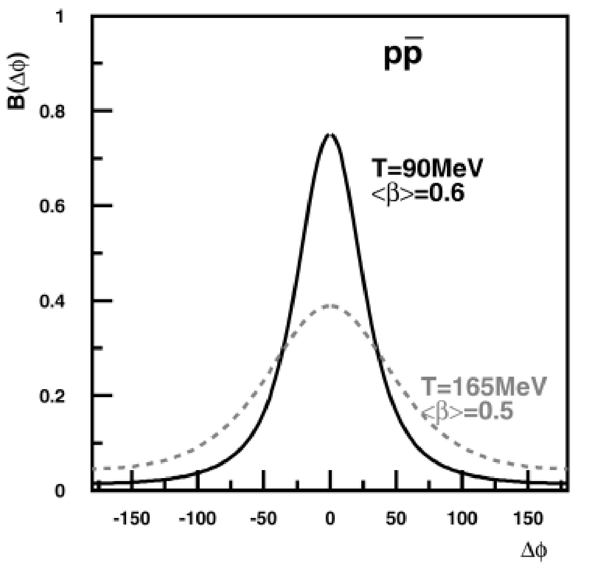

Fig. 4. The proton-antiproton balance function in azimuthal angle.

particles stay in contact with the local thermal source where they are created. The momenta of the pair follow the thermal history of the local source on its way to the kinetic freeze-out. At the decoupling, relative particle momenta correspond to a thermal emission from a source having a low kinetic freeze-out temperature.

In the calculation for the single freeze-out model, 30% of the pions come from the decay of neutral resonances. At the low temperature corresponding to the blast wave parameterisation, this contribution can be neglected. The rest of the pions is taken as emitted thermally from a local source. The details of the calculation can be found in Refs. [4] and [5]. In Fig. 3 is shown the charge balance function in azimuthal angle for pions. Different freeze-out conditions yield very different azimuthal correlations. The high freeze-out temperature and the moderate flow lead to a broad correlation peak in the case of the single freeze-out model. This effect is enhanced by the contribution from resonance decays which has a broad azimuthal correlation due to the back to back emission in a two body decay in the rest frame of the resonance. The situation is different for the blast wave parameters, first, the contribution of resonances is negligible, and second, due to a smaller temperature and larger velocity of the source the particles are emitted in a narrow cone in azimuthal angle.

In Fig. 4, the results for the proton-antiproton balance function are shown. Qualitatively the effect is similar as for pions. The emission at a higher temperature and with a smaller transverse flow leads to pairs less collimated in azimuthal angle. Resonance decays does not modify the result for protons. Due to the larger mass, proton-antiproton correlations could serve as a precise quantitative measure of the relative importance of the thermal and collective flow, enabling an unambiguous extraction of the flow parameters at freeze-out.

Above, we have discussed the angle averaged charge balance function $B(\delta\varphi)$. Let us consider the balance function $B(\delta\varphi,\varphi)$ as in Eq. (1), which is sensitive to the direction of the emission of the pair. The dependence of the balance function on the angle could originate from an angular dependence of the freeze-out temperature or flow velocity. An azimuthally dependent transverse flow is usually introduced to describe the elliptic flow observed in collisions with non-zero impact parameters [9]. The observed elliptic flow is a result of a combination of an asymmetry in momentum space (transverse flow asymmetry) and of an asymmetry of the geometry of the source. The last one can be accessed independently by azimuthally sensitive HBT measurements. The asymmetry in the transverse flow would result in an angular dependent correlation structure in the charge balance function. Pairs emitted in-plane originate from local sources with a larger flow and the width of the charge balance function should be smaller than for pairs emitted out of plane. In Fig. 5 the charge

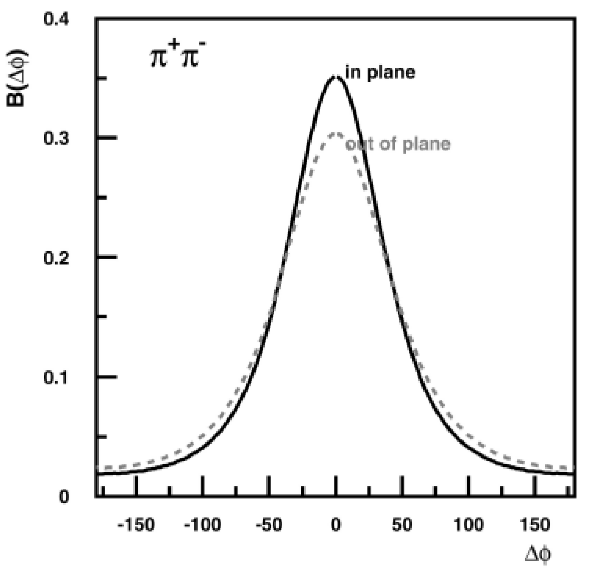

Fig. 5. The pion charge balance function in azimuthal angle for pairs emitted in-plane (solid line) and out of plane (dashed line).

balance function is shown for pions from events of centrality 50–60%. The temperature, flow profile and asymmetry are taken from blast wave fits to the data [1]. In-plane (out of plane) pairs are taken when the first particle is emitted in the direction from –45 to 45 degrees from the in plane (out of plane) direction.

The effect of a stronger flow in plane is clearly visible, and could be verified experimentally. However, the asymmetry between the flow in and out of plane is small and the resulting differences in the charge balance functions are moderate.

The measurements of spectra of particles produced in heavy-ion reaction and at the same time of balance functions in azimuthal angle give an uncorrelated estimate of the freeze-out temperature and of the average transverse flow. The effect of an increase of the temperature together with a decrease of the transverse flow compensate to a large extend in the transverse momentum spectra. On the other hand, both the increase of the temperature and the decrease of the flow make the charge correlations in azimuthal angle wider. The measurement of the width in the relative angle of two opposite charged particles is a strong constraint on the amount of the transverse flow in the reaction. Azimuthally sensitive charge balance functions offer the unique possibility to observe the asymmetry in the transverse flow independently of the geometrical asymmetry of the source.

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