Charge conservation and the shape of the ridge of two-particle correlations in relativistic heavy-ion collisions

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We demonstrate that in the framework of the event-by-event hydrodynamics followed by statistical hadronization, the proper charge conservation in the mechanism of hadron production provides the crucial non-flow component and leads to agreement with the two-dimensional two-particle correlation data in relative azimuthal angle and pseudorapidity at soft transverse momenta ($p_T < 2$ GeV). The fall-off of the same-side ridge in relative pseudorapidity follows from the fact that a pair of particles with balanced charges is emitted from the same fluid element, whose collective velocity collimates the momenta of the pair. We reproduce basic experimental features of the two-dimensional correlation function, such as the dependence on the relative charge and centrality, as well as the related charge balance functions and the harmonic flow coefficients as functions of the relative pseudorapidity.

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Two-particle correlation functions in the relative angle $\Delta \phi$ and pseudorapidity $\Delta \eta$ are valuable tools to study collective flow and the mechanism of particle emission in relativistic heavy-ion collisions. The harmonic components of the collective flow are visible in the dihadron correlation function as two ridge structures on the same ($\Delta \phi \simeq 0$) and away ($\Delta \phi \simeq \pi$) sides \cite{1}. There is, however, an on-going discussion concerning the puzzling nature of the same-side ridge \cite{2}. While it is commonly accepted that the collective harmonic flow \cite{3} determines the profile in $\Delta \phi$ for large pseudorapidity separations, up to now the shape of these structures in $\Delta \eta$, in particular the rather fast fall-off of the same-side ridge, remains an object of active debate, with arguments that the presence of (minil)jets \cite{3} is essential to explain the phenomenon and that the applicability of hydrodynamics, reproducing numerous other features of the heavy-ion data, is at stake. Thus the issue is of great importance for the fundamental understanding of relativistic heavy-ion collisions. Other attempts to explain the nature of the ridge can be found in Refs. \cite{4}.

In this Letter we show that two basic features of the two-particle correlations get a quantitative explanation via the charge balance mechanism of particle emission: 1) the shape of the same-side ridge in $\Delta \eta$, and 2) the difference between the correlation functions for like- and unlike-sign particles. Thus we explain the ridge puzzle in a natural way, amend the (event-by-event, 3+1-dimensional, viscous) hydrodynamics with the local charge-conservation mechanism in the statistical hadronization occurring after the hydrodynamic evolution. This important charge balancing \cite{3,4}, simply stating that the hadron production conserves locally the charge, is an otherwise well-known and measured feature.

The results presented in this work concern “soft physics” (typically with the transverse momentum of all particles $p_T < 2$ GeV) and unbiased correlations, where the kinematic cut on both particles is the same. The relevant correlation function is determined as

\begin{equation}
C(\Delta \eta, \Delta \phi) = \frac{N_{\text{real}}^{\text{pair}}(\Delta \eta, \Delta \phi)}{N_{\text{mixed}}^{\text{pair}}(\Delta \eta, \Delta \phi)}, \quad (1)
\end{equation}

where $N_{\text{real}}^{\text{pair}}(\Delta \eta, \Delta \phi)$ denote the two-dimensional distributions of pairs of particles with relative pseudorapidity $\Delta \eta$ and azimuth $\Delta \phi$, obtained from the real and mixed events, respectively. Our approach consists of using GLISSANDO \cite{3} to generate the Glauber-model initial condition, then running event-by-event 3+1D hydrodynamics with shear and bulk viscosities \cite{10}, and finally carrying out the statistical hadronization with THERMINATOR \cite{11} at the freeze-out temperature $T_f$. Our simulations incorporate the kinematic cuts of the STAR experiment, with $|\eta| < 1$, appropriate $p_T$ cuts specified later, as well as the detector efficiency at the level of

![FIG. 1. (Color online) A schematic view of the charge balancing mechanism, producing pairs of particles with opposite charges. The rectangles indicate fluid elements moving outward with a collective velocity $u$. The dot indicates the space-time location of the emission of the pair of opposite-charge particles of momenta $p_1$ and $p_2$. The dashed line represents a neutral resonance, decaying into a pair particles.](image-url)
90%, estimated to hold for the registered charged particles in STAR. For simplicity, we set all chemical potentials at freeze-out to zero, which is a good approximation at RHIC. Other, more technical details of our approach may be found in Ref. [10].

The observed charge balance functions can be explained assuming that opposite charge pairs are created towards the end of the evolution [6, 7]. To implement this mechanism in a simple model way but with a realistic hydrodynamic flow (we call it direct charge balancing), we enforce that the same-species charged hadron-antihadron pairs are produced at the same space-time location \( x \) (see Fig. 1). The hadron momenta \( p_1 \) and \( p_2 \) are determined independently according to the Cooper-Frye formula. The fact that the fluid element moves with a collective velocity \( u^\mu(x) \) causes a certain-degree of collimation of the momenta of the produced pair. An additional balancing mechanism comes from the decays of neutral resonances (see Fig. 1). The correlations induced by balancing are of a non-flow character, i.e., cannot be obtained by the folding of single-particle distributions containing the collective flow.

To illustrate the relevance of the effect, in Fig. 2 we show the results of our simulations for several cases for the like-sign \((+,−)\) and unlike-sign \((++,−−)\) pairs. In panel (a) we show the correlation \( C(++,−−) \) without direct balancing. We note the completely flat ridges, reflecting the approximate boost-invariance in the investigated kinematic range and, of course, the presence of flow. We use the framework of event-by-event viscous hydrodynamics which generates realistic elliptic and triangular flows in the collisions [12]. Therefore the dominant modulation of the shape in azimuth of the elliptic and triangular flows is well reproduced [1, 13]. Panel (b) shows the same for \( C(−+) \), where some mild fall-off in \( \Delta \eta \) of the same-side ridge follows from the resonance decays. Panels (c) and (d) include the direct charge balancing. We now note a prominent fall-off of the same-side ridge in \( C(−+) \), which is our key observation: the quantity \( C(−+)-1 \) drops from the central region to \( |\Delta \eta| = 2 \) by about a factor of 2. The fall-off is also enhanced for \( C(++,−−) \) due to secondary effects from balancing of heavier particles, which later decay. The results of panels (c,d) are in qualitative and approximate quantitative agreement to the results of the STAR Collaboration, where the HBT correlations for identical particles are subtracted [2].

To check whether our mechanism is correct also at the quantitative level, we now proceed to the investigation of the charge balance functions, defined as \( B(\Delta \eta) = \langle N_{−+-} − N_{++} \rangle/\langle N_+ \rangle + \langle N_{−−} − N_{−+} \rangle/\langle N_- \rangle \), where \( \langle N_{ab} \rangle \) denotes the event-averaged distributions of particles \( a \) and \( b \) with relative rapidity \( \Delta \eta \), and \( \langle N_\alpha \rangle \) stands for the average number of particles \( a \) in the acceptance window \( |\eta| < 1 \). We note that the charge balance function is related to the distributions in the numerator of Eq. (1),

\[
B(\Delta \eta) = \frac{\left[ d\Delta \phi[N_{++}^{\text{pair}}(\Delta \eta, \Delta \phi) − N_{++}^{\text{pair}}(\Delta \eta, \Delta \phi)]\right]}{2\pi\langle N_+ \rangle} + \quad (+ \leftrightarrow −).
\] (2)

The outcome, with correct agreement to the data, is presented in Fig. 3. We note a preference to the lower freeze-out temperature, \( T_f = 140 \) MeV.
The next quantitative investigation concerns the dependence of the flow coefficients on $\Delta\eta$, defined as

$$v_2^2(\Delta\eta) = \int d\Delta\phi \cos(n\Delta\phi)C(\Delta\eta, \Delta\phi).$$  

(3)

The projection on the $\Delta\eta$ axis of the different harmonics yields the squares of the consecutive flow components $v_2$ present in the dihadron correlation functions. The results presented in Fig. 4 show agreement with the experiment, best for the mid-peripheral collisions and $T_f = 140$ MeV.

For the peripheral collisions, where the hydrodynamic approach is less justified, the agreement is qualitative, indicating that the hydrodynamic calculation overestimates the elliptic flow for large centralities. The experimental bands are extracted by integrating a model function fit to the measured dihadron correlations [2], varying the fit parameters within the estimated uncertainty. We note that these uncertainties are large for the central and peripheral cases. Our simulations incorporating the direct charge balancing (thick lines) exhibit the expected fall-off with $|\Delta\eta|$, while the cases without direct balancing (thin lines) are flat. The independence of $v_2^2$ on $\Delta\eta$ for the emission without charge balancing reflects the approximate pseudorapidity independence of the collective flow in the considered kinematic window. Charge balancing induces an additional component in $C$, of limited range $|\Delta\eta| \simeq 1$. The collimation of the opposite charge pairs occurs in the relative angle as well [8, 14]. As a result, the contribution from charge balancing in $C(\Delta\eta, \Delta\phi)$ acquires the form of a 2-dimensional peak at $\Delta\eta = \Delta\phi = 0$. The shape in $\Delta\eta$ of the non-flow component in $v_2^2$ is qualitatively reproduced in the simulations, but the overall strength is somewhat larger than extracted from the model fit in [2]. Thus our study shows that the charge balancing is the non-flow source of the observed $\Delta\eta$ dependence of the flow coefficients [15]. The qualitatively similar behavior of higher-order harmonics, which needs higher statistics in our simulation, as well as $v_3^2$, where the effects of the transverse-momentum conservation (not included in the present study) are important [16], will be presented elsewhere.

One may also compare the correlation function $C$ directly to the data shown, e.g., in Figs. 1 and 2 of Ref. [17], obtained for $0.8 < p_T < 4$ GeV, and with the HBT peak for the same-sign pairs removed. Our simulations shown in Fig. 5 display, for the first time in an approach based on hydrodynamics, all qualitative features of the data and remain also in fair quantitative agreement. In particular, we note the proper dependence on the relative charge and centrality. Notably, the combinations $C(+-) - C(++,--)$ obtainable from Fig. 5 exhibit no ridges whatsoever, as they cancel out, leaving the central peak as the only structure.

In conclusion, we remark that the presented simple effect based on the local charge conservation in the hadronization process is generic in its nature. It
should manifest itself in all approaches where the charge balancing is combined with a collective motion of the source. Our approach, based on the fluctuating Glauber-model initial conditions, state-of-the-art hydrodynamics, and statistical hadronization incorporating the direct charge balancing, is capable of reproducing all basic features of the data for the unbiased correlation function $C(\Delta \eta, \Delta \phi)$, as well as for the related quantities, such as the charge balance function and the harmonic flow coefficients $v_2^{n}(\Delta \eta)$. The correlation from charge balancing, yielding a two-dimensional central peak, comes on top of the ridge structures following from the presence of the azimuthally asymmetric collective flow [1]. It thereby brings in a crucial non-flow component in the harmonic flow coefficients $v_2^{n}$, with a characteristic fall-off in the relative pseudorapidity. Thus the collective flow together with the local charge conservation is the key to a successful explanation of the shape of the correlation data in relativistic heavy-ion collisions.

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FIG. 5. (Color online) Our simulations for the correlation function $C$ with direct charge balancing included for the like-sign (a,b,c) and unlike-sign (d,e,f) pairs at three sample centralities ($T_f = 140$ MeV, $0.8 < p_T < 4$ GeV as in Ref. [17]).