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 nonflow 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 falloff 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 azimuth $\Delta\phi$ and pseudorapidity $\Delta\eta$ are valuable tools to study collective flow and the mechanisms of particle emission in relativistic heavy-ion collisions, with the long-range component probing very early times. The appearance of the longitudinal long-range correlation in proton-proton collisions can be explained, e.g., in the framework of the color-glass condensate [1]. Such correlations are implicitly assumed in the initial condition for the hydrodynamic evolution in heavy-ion collisions, which subsequently generates the harmonic components of the transverse flow, visible in the dihadron correlation function as two *ridge* structures on the same ($\Delta\phi \simeq 0$) and away ($\Delta\phi \simeq \pi$) sides [2]. There is, however, an ongoing discussion concerning the puzzling nature of the same-side ridge [3]. In particular, its rather fast falloff in $\Delta\eta$ remains an object of active debate, with arguments that the presence of (mini)jets [4] 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.

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: (i) the shape of the same-side ridge in $\Delta\eta$ and (ii) the difference between the correlation functions for like- and unlike-sign particles. Thus we explain the ridge puzzle in a natural way, amending 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* [5–8], 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

$$C(\Delta\eta, \Delta\phi) = N^{\mathrm{pair}}_{\mathrm{real}}(\Delta\eta, \Delta\phi)/N^{\mathrm{pair}}_{\mathrm{mixed}}(\Delta\eta, \Delta\phi), \quad (1)$$

where $N^{\mathrm{pair}}_{\mathrm{real,mixed}}(\Delta\eta, \Delta\phi)$ 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 [9] to generate the Glauber-model initial condition fluctuating in the transverse plane, then running event-by-event (3 + 1)D hydrodynamics with shear and bulk viscosities [10], and finally carrying out the statistical hadronization with THERMINATOR [11] at the freeze-out temperature T_f. For every centrality we generate 100 initial configurations, and for each we produce 2000 events to improve the statistics. 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 90%, estimated to hold for the registered charged particles in STAR. We set all chemical potentials at freeze-out to zero, which is a good approximation at the Relativistic Heavy Ion Collider. In the considered $\Delta\eta < 1$ window, the dependence of v_2 and v_3 on η is flat [in that regard, one could even use the (2 + 1)D event-by-event hydrodynamics here], and as such it cannot explain the observed falloff of the ridge. Moreover, the charge dependence would not be manifest. The use

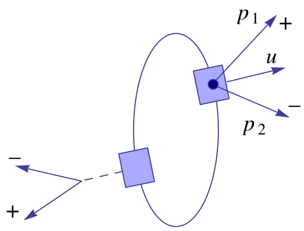

FIG. 1 (color online). A schematic view of the charge balancing mechanism, producing pairs of particles with opposite charges. The rectangles indicate fluid elements moving outward with a collective velocity u. The dot indicates the space-time location of the emission of the pair of opposite-charge particles of momenta p_1 and p_2. The dashed line represents a neutral resonance, decaying into a pair particles.

of viscous hydrodynamics helps in simultaneous description of v_2 and v_3 (within a few percent) in our approach.

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 nonflow 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 Fig. 2(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 [2,13]. Figure 2(b) shows the same for $C(+-)$, where some mild falloff in $\Delta\eta$ of the same-side ridge follows from the resonance decays. Figures 2(c) and 2(d) include the direct charge balancing. We now note a prominent falloff 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 falloff is also enhanced for $C(++,--)$ due to secondary effects from balancing of heavier particles, which later decay. The results of Figs. 2(c) and 2(d) are in semiquantitative agreement with the results of the STAR Collaboration, where the Hanbury Brown–Twiss correlations for identical particles are subtracted [3].

To check if 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

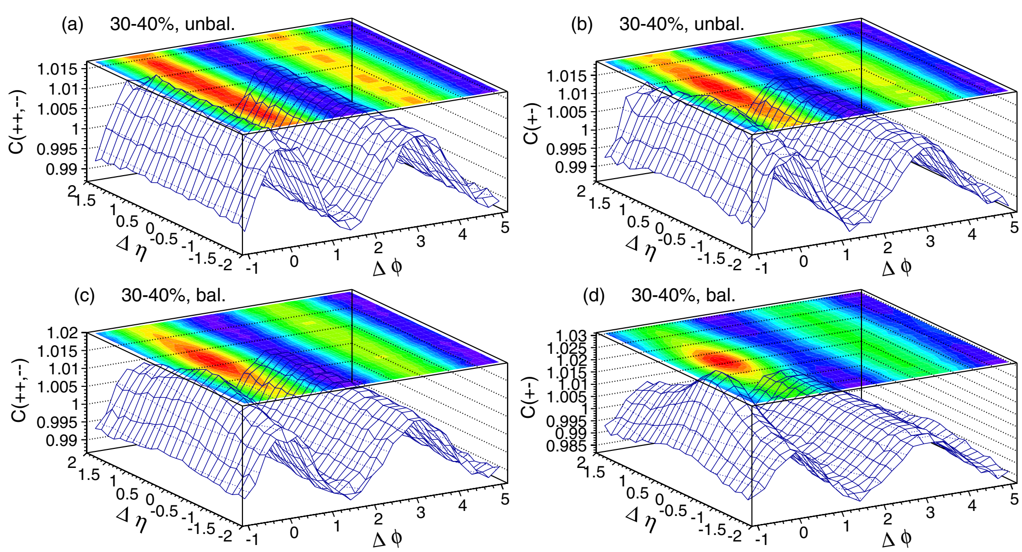

FIG. 2 (color online). The correlation function C for like-sign (a),(c) and opposite-sign (b),(d) pairs. Panels (a),(b) and (c),(d) correspond to absent and present direct charge balancing, respectively. Inclusion of charge balancing sharpens the peak around $\Delta\eta = \Delta\phi = 0$ and causes the desired falloff of the same-side ridge (centrality 30%–40%, $T_f = 140$ MeV, $0.2 < p_T < 2$ GeV).

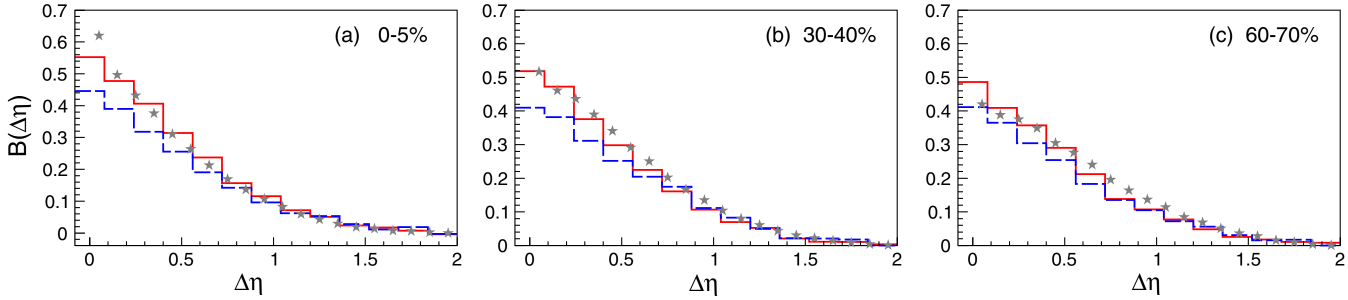

FIG. 3 (color online). The charge balance function for $T_f = 140$ (solid lines) and 150 MeV (dashed lines). The stars indicate the STAR measurement at $\sqrt{s_{NN}} = 200$ GeV [8] ($0.2 < p_T < 2$ GeV, efficiency 90%).

b with relative rapidity $\Delta\eta$ and $\langle N_a\rangle$ stands for the average number of particles a in the acceptance window $|\eta| < 1$. The charge balance function

$$B(\Delta\eta) = \frac{\int d\Delta\phi[N^{\rm pair}_{+-}(\Delta\eta,\Delta\phi) - N^{\rm pair}_{++}(\Delta\eta,\Delta\phi)]}{2\pi\langle N_+\rangle} + (+ \leftrightarrow -) \tag{2}$$

is related to the distributions in Eq. (1). 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. Nonzero bulk viscosity at freeze-out reduces the thermal motion of emitted particles and is equivalent to lowering the freeze-out temperature, yielding a stronger collimation on unlike-sign pairs.

The next quantitative investigation concerns the dependence of the flow coefficients on $\Delta\eta$, defined as

$$v_n^2(\Delta\eta) = \int \frac{d\Delta\phi}{2\pi}\cos(n\Delta\phi)C(\Delta\eta,\Delta\phi). \tag{3}$$

The projection on the $\Delta\eta$ axis of the different harmonics yields the squares of the consecutive flow components v_n present in the dihadron correlation functions. The results presented in Fig. 4 show agreement with the experiment, best for the midperipheral 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 [3] and 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 quested falloff with $|\Delta\eta|$, while the cases without direct balancing (thin lines) are flat. The independence of v_n^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 two-dimensional peak at $\Delta\eta = \Delta\phi = 0$. The shape in $\Delta\eta$ of the nonflow component in v_3^2 is qualitatively reproduced in the simulations, but the overall strength is somewhat larger than extracted from the model fit in Ref. [3]. Also, one can notice that the agreement deteriorates for peripheral collisions, which is at the boundary of applicability of hydrodynamics. Our study shows that the charge balancing is the nonflow source of the observed $\Delta\eta$ dependence of the flow coefficients [15]. The qualitatively similar behavior of higher-order harmonics, which needs

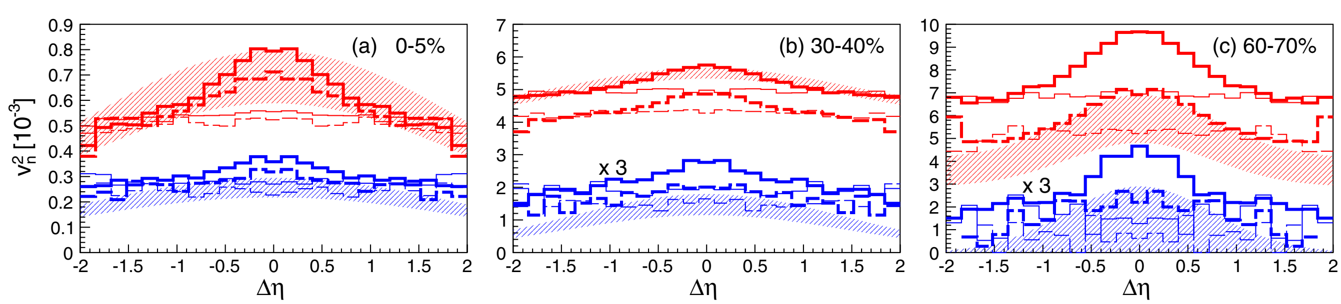

FIG. 4 (color online). The flow coefficients v_2^2 (top lines) and v_3^2 [bottom lines, in (b) and (c) multiplied by 3]. Simulations with direct charge balancing are drawn with thick solid ($T_f = 140$ MeV) and dashed lines ($T_f = 150$ MeV), while the corresponding reference simulations without direct charge balancing are drawn with thin lines. The dashed bands are extracted from the fits to experimental data reported by STAR in Table I of Ref. [3] ($0.15 < p_T < 4$ GeV, as in the experiment).

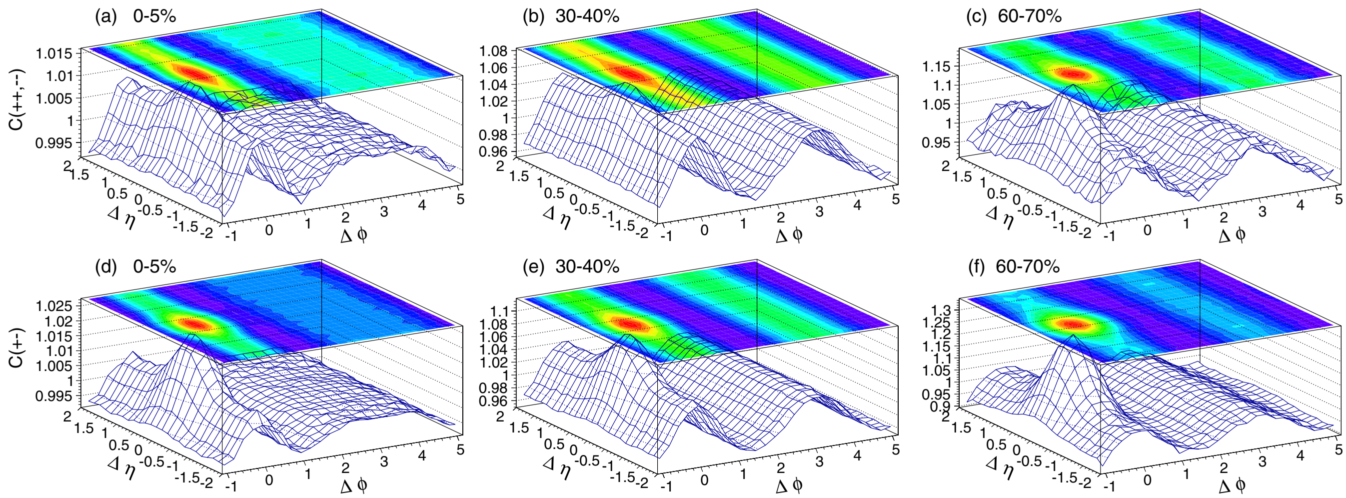

FIG. 5 (color online). Our simulations for the correlation function C with direct charge balancing included for the like-sign (a)–(c) and unlike-sign (d)–(f) pairs at three sample centralities ($T_f = 140$ MeV, $0.8 < p_T < 4$ GeV as in Ref. [17]).

higher statistics in our simulation, as well as v_1^2, 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 Hanbury Brown–Twiss peak for the same-sign pairs removed. Our simulations 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. We note the proper dependence on the relative charge and centrality. Notably, the combinations $C(+-) - C(++, --)$ 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 is generic and should manifest itself in all approaches where 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 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 $v_n^2(\Delta\eta)$. 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 [2]. It thereby brings in a crucial nonflow component in the harmonic flow coefficients v_n^2, with a characteristic falloff 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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