Azimuthal angle dependence of the charge imbalance from charge conservation effects

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(Dated: October 5, 2018)

The experimental search for the chiral magnetic effect in heavy-ion collisions is based on charge dependent correlations between emitted particles. Recently, a sensitive observable comparing event-by-event distributions of the charge splitting projected on the directions along and perpendicular to the direction of the elliptic flow has been proposed. The results of a 3+1-dimensional hydrodynamic model show that the preliminary experimental data of the STAR Collaboration can be explained as due to background effects, such as resonance decays and local charge conservation in the particle production. A related observable based on the third order harmonic flow is proposed to further investigate such background effects in charge dependent correlations.

I. INTRODUCTION

The possibility of creating topological domains with a non-zero topological charge in the dense matter created in heavy-ion collisions has been proposed [1,2]. In the presence of a magnetic field, as in the early stages of the collision, this would induce an event-by-event charge separation between emitted particles, the chiral magnetic effect. The charge splitting between same-sign and unlike-sign pairs in a specific correlator has been proposed as a sensitive observable to discover the presence of topological domains [3].

The chiral magnetic effect has been searched for experimentally in heavy-ion collisions [4-9]. One observes a charge dependence in two-particle correlations with respect to the second order harmonic flow. On the other hand, many of these observations are quantitatively explained as due to standard charge correlations present in particle production [10,13]. The simplest example of such correlation is given by the correlation between decay products of resonances. The phenomenon is generic and any particle formation mechanism should obey charge conservation constraints. Local charge conservation leads to correlation between unlike-signed particles in phase-space [14]. As a result two-particle correlation in rapidity and/or azimuthal angle show a definite charge dependence [15-17].

Recently, a new observable has been proposed as a measure of charge dependent splitting along the direction of the magnetic field. The event-by-event distribution of the charge splitting projected on the direction of the magnetic field (perpendicular to the elliptic flow direction) is compared between real events and events with randomized charges [18]. A more sensitive observable is constructed as the ratio of the event-by-event distributions of charge splitting perpendicular and along the direction of the elliptic flow [19]. It has been noticed that the effect observed in preliminary data of the STAR Collaboration [20] is qualitatively different from models without a chiral magnetic effect.

In this paper I calculate the distribution of the charge splitting in a 3+1-dimensional hydrodynamic model for A+A and p+Pb collisions. I show that in simulations involving correlations between charged particles from resonance decays or local charge conservation [17] the experimental data are qualitatively reproduced, i.e. the charge splitting distribution is wider out-of-plane than in-plane. A similar observable is proposed involving the third order event-pane. In this new observable any charge dependence of the correlations comes solely from the triangular flow, without any contribution from the chiral magnetic effect. This observable could give as an additional test of possible background effects in the search for QCD topological domains in heavy-ion collisions.

II. EVENT-BY-EVENT DISTRIBUTION OF THE CHARGE SPLITTING

Simulations are performed in a 3 + 1-dimensional viscous hydrodynamic model [21,22]. After the expansion of the fireball, particles are emitted statistically from the freeze-out hypersurface, defined as the surface of constant temperature \( T = 150 \text{ MeV} \). In the standard implementation, particles are emitted independently [23]. For particles directly emitted from the freeze-out hypersurface (primordial particles) no charge dependent correlations are present. Charge correlations are build in only from subsequent decay of resonances. In the model with local charge conservation particles are emitted in pairs from the same fluid element, a particle and the corresponding antiparticle. The particle and antiparticle share the common flow velocity of the fluid and have an independent thermal component of the momentum. This simple model encompasses the collimation effect between opposite charges from the collective flow [17].

The calculation of the correlation sensitive to the chiral magnetic effect requires a large statistics. In the following I show selected centralities for Pb+Pb collisions at \( \sqrt{s} = 2760 \text{ GeV} \) and p+Pb collisions at \( \sqrt{s} = 5020 \text{ GeV} \), both using a quark Glauber Monte Carlo model for the hydrodynamic initial conditions [24], as well as for
Au+Au collisions at $\sqrt{s} = 200$ GeV using a nucleon Glauber model for initial conditions [22]. All the calculations are performed in two versions, one with charge correlations from resonance decays only and the other including also the local charge conservation effect. The details of the initial conditions and of the hydrodynamic modeling are not essential for the present study as long as the spectra and the average harmonic flow coefficients are reproduced. The charge splitting background effects discussed in this paper involve phenomena happening at the freeze-out and after. The hydrodynamic evolution is needed to obtain a realistic freeze-out hypersurface and flow. Alternatively, a simple blast-wave ansatz has been successfully used instead [12].

The chiral magnetic effect leads to a charge separation along the direction of the magnetic field. As the direction of the magnetic field is perpendicular to the direction of the second order event plane $\Psi_2$, the presence of topological effects should lead to an increase of the magnitude of the charge splitting projected on a direction perpendicular to $\Psi_2$ [18]

$$\Delta S = \frac{\sum_{i=1}^{p} \sin(\phi_i - \Psi_2)}{p} - \frac{\sum_{i=1}^{m} \sin(\phi_i - \Psi_2)}{m}. \quad (1)$$
The sums go over all the $p$ positive and $m$ negative charges in the acceptance region ($\eta < 1$, $0.15 \text{ GeV} < p_{\perp} < 2 \text{ GeV}$). The magnitude and the sign of $\Delta S$ vary from event to event. The distribution $N(\Delta S)$ of $\Delta S$ is constructed. From real events reshuffled events are generated by reshuffling the charges of particles in the acceptance region. The corresponding distribution is $N_{sh}(\Delta S)$. The ratio of the two distributions is

$$C(\Delta S) = \frac{N(\Delta S)}{N_{sh}(\Delta S)}.$$  \hspace{1cm} (2)

The same ratio is constructed for the charge splitting projected on the direction perpendicular to the magnetic field

$$\Delta S_\perp = \frac{\sum_{i=1}^p \cos(\phi_i - \Psi_2) - \sum_{i=1}^m \cos(\phi_i - \Psi_2)}{p},$$  \hspace{1cm} (3)

with the corresponding correlation $C_\perp(\Delta S_\perp)$. Finally, the correlator involving the ratio of the two correlations is calculated \[19\]

$$R(\Delta S) = \frac{C(\Delta S)}{C_\perp(\Delta S)}.$$  \hspace{1cm} (4)

The authors of Ref. \[19\] notice that in a model with a chiral magnetic effect and in the preliminary STAR data $R(\Delta S)$ has a convex shape, while in other models studied it has a concave shape.

The correlator $R(\Delta S)$ in Pb+Pb collisions is shown in Fig. 1. In all panels three results are compared, one using a model with local charge conservation and resonance decays, one from a model with resonances only, and one from a model where only primordial particles are taken. In the calculation the second order event-plane direction $\Psi_2$ is reconstructed from combined events, involving many statistical events generated from the same freeze-out hypersurface. Thus the event plan resolution is close to one. However, the charge splitting $\Delta S$ (Eq. 1) is calculated from real events with a realistic multiplicity.

As expected, primordial particles show no charge dependent correlations. The other two calculations show a convex shape for the function $R(\Delta S)$. The model with local charge conservation shows a stronger charge dependence of the correlator than the model with resonances only, except for the centrality $0 - 5\%$ where the two are compatible within errors. The convex-like deviation of the correlator $R(\Delta S)$ from 1 is the strongest in semi-central and peripheral collisions. Due to the elliptic flow, the azimuthal dependence of the fluid flow velocity is the strongest in these cases. The stronger the flow the more collimated are opposite-charged particle pairs from resonance decays and from the local charge conservation. Qualitatively, similar results are obtained for p+Pb (Fig. 2) and Au+Au collisions (Fig. 3). The range of $\Delta S$ increases with decreasing average multiplicity in the events.

FIG. 4. (color online) In- and out-of-plane charge imbalance distributions for Au+Au collisions at $\sqrt{s} = 200 \text{ GeV}$ and centrality $30 - 40\%$.

### III. DISTRIBUTION OF THE CHARGE IMBALANCE IN- AND OUT-OF-PLANE

The STAR Collaboration presented a related study, comparing the distribution of the charge imbalance in the directions in- and out-of-plane \[9\]. The in-plane charge imbalance is defined as

$$\Delta Q_{\text{in}} = Q_I - Q_{III},$$  \hspace{1cm} (5)

where $Q_I$ and $Q_{III}$ denote the total charge of particles registered in the quadrants $\Psi_2 - \frac{\pi}{2} < \phi < \Psi_2 + \frac{\pi}{2}$ and $\Psi_2 + \frac{\pi}{2} < \phi < \Psi_2 + \frac{3\pi}{2}$. Analogously for the out-of-plane direction

$$\Delta Q_{\text{out}} = Q_{II} - Q_{IV},$$  \hspace{1cm} (6)

where $Q_{II}$ and $Q_{IV}$ denote the total charge of particles registered in the quadrants $\Psi_2 + \frac{\pi}{2} < \phi < \Psi_2 + \frac{3\pi}{2}$ and $\Psi_2 + \frac{3\pi}{2} < \phi < \Psi_2 + \frac{5\pi}{2}$.

The event-by-event distributions of the charge imbalances $\Delta Q_{\text{in}}$ and $\Delta Q_{\text{out}}$ are shown in Fig. 4. The in-plane charge imbalance is narrower than the out-of-plane one. The relative difference of the rms values for the two distributions

$$\frac{\text{RMS}_{\text{out}} - \text{RMS}_{\text{in}}}{(\text{RMS}_{\text{out}} + \text{RMS}_{\text{in}})/2} = 0.022$$  \hspace{1cm} (7)

is close to the experimental value $0.019$ \[9\].

### IV. CHARGE SPLITTING DISTRIBUTION WITH RESPECT TO THE THIRD ORDER EVENT PLANE

The azimuthal asymmetry of the collective flow contains a third order component, the triangular flow. The charge dependent correlations depend on the flow and
should exhibit a modulation with respect to the angle of the third order flow component $\Psi_3$. The directions of the minimal flow are located at $\Psi_3 \pm \pi/3$ and $\Psi_3 + \pi$. The projection of the charge splitting on the direction of minimal flow can be defined as

$$\Delta S_3 = \frac{\sum_{i=1}^{p} \sin \left( \frac{3}{2} (\phi_i - \Psi_3) \right)}{p} - \frac{\sum_{i=1}^{m} \sin \left( \frac{3}{2} (\phi_i - \Psi_3) \right)}{m}$$

(8)

FIG. 5. (color online) Same as in Fig. 1 but for the third order event plane (Eq. 10).

and analogously for the directions along the flow

$$\Delta S_{\perp,3} = \frac{\sum_{i=1}^{p} \cos \left( \frac{3}{2} (\phi_i - \Psi_3) \right)}{p} - \frac{\sum_{i=1}^{m} \cos \left( \frac{3}{2} (\phi_i - \Psi_3) \right)}{m}$$

(9)

The events-by-event distributions of $\Delta S_3$ and $\Delta S_{\perp,3}$ are constructed for the real and reshuffled events to obtain the distributions $C_3(\Delta S_3)$ and $C_{\perp,3}(\Delta S_{\perp,3})$. Finally the correlator for the charge splitting with respect to the third order flow is calculated

$$R_3(\Delta S_3) = \frac{C_3(\Delta S_3)}{C_{\perp,3}(\Delta S_3)}$$

(10)

The results for the third order correlator are shown in Figs. 5, 6, and 7. The convex deviation of the third order correlator $R_3(\Delta S_3)$ from 1 is visible for semi-central and peripheral collisions of heavy ions, although the effect is less pronounced than for the second order correlator $R(\Delta S)$. For central Pb+Pb collisions and for p+Pb collisions no significant deviation of the correlator from 1 can be evidenced.
V. EVENT PLANE RESOLUTION EFFECTS

The calculation of the charge splitting with respect to \( \Psi_2 \) and \( \Psi_3 \) requires the reconstruction of the corresponding event planes. In the model the deviation of the reconstructed events plane \( \Psi_{2,3}^{\text{flow}} \) from the true flow direction can be estimated. The actual result depends on the particular definition of the event plane in the experimental procedure. For illustration, one case is studied, defining the event plane from 50% of charged particles with \( 2 < |\eta| < 4 \) and \( 0.15 \text{ GeV} < p_{\perp} < 2 \text{ GeV} \). Finite event-plane resolution is expected to reduce to relative differences between correlations for the in- and out-of-plane directions.

Another aspect of the procedure, that influences the \( \Delta S \) and \( \Delta S_3 \) distributions is the choice of the acceptance window for charged particles used in the analysis and the corresponding efficiency. By reducing the acceptance window or by lowering the efficiency the distributions of \( \Delta S \) and \( \Delta S_3 \) get broader. In this section we keep the same acceptance window as before ((|\eta| < 1, 0.15 \text{ GeV} < p_{\perp} < 2 \text{ GeV}) but with an efficiency of 80%.

The results of the calculation for \( R(\Delta S) \) including the effect of finite event-plane resolution are plotted in Figs. 8 and 9. Qualitatively, the results are not modified by a finite event-plane resolution, but the deviation of the correlator from 1 is smaller. The third order correlator \( R_3(\Delta S) \) is more sensitive to a finite event-plane resolution. The signal is weaker for \( R_3 \) and the event-plane resolution is usually much poorer for the triangular than for the elliptic flow. The deviation of the third order correlator from 1 is strongly reduced, or could be even washed out by event-plane resolution effects (Figs. 10 and 11). In order to measure \( R_3(\Delta S_3) \) a setup allowing for a good event-plane resolution should be used.
VI. CONCLUSIONS

A correlator $R(\Delta S)$ (Eq. 4) comparing the event-by-event charge splitting in the directions along and perpendicular to the magnetic field in heavy-ion collisions has been proposed as a sensitive probe of the chiral magnetic effect [19]. The presence of topological domains in the deconfined phase should lead to an enhanced charge splitting in the direction of the magnetic field giving a convex shape of $R(\Delta S)$. I show that qualitatively the same behavior can be reproduced due to standard charge correlations, such as resonance decays and local charge conservation. The results of 3+1-dimensional hydrodynamic simulations in Pb+Pb, p+Pb, and Au-Au collisions show all a convex shape of $R(\Delta S)$.

The results show that a convex shape of the charge splitting observable $R(\Delta S)$ cannot be used and unambiguous evidence of the chiral magnetic effect in heavy-ion collisions. The background effects from standard phenomena give a very large contribution to this observable. It would be very challenging to calculate reliably and subtract the background contribution from the measured correlator in order to extract a possible signal of the chiral magnetic effect.

If charge dependent correlations are due to resonance decays and/or local charge conservation the charge splitting should have a third order azimuthal dependence from the triangular flow. Simulations predict such an effect. This new observable could be measured in experiments that have a good event-plane resolution. It would give an additional constraint on the background effects present in the observables sensitive to the chiral magnetic effect.

ACKNOWLEDGMENTS

The author thanks Adam Bzdak, Sandeeep Chatterjee, and Roy Lacey for discussions. Research supported by the Polish Ministry of Science and Higher Education (MNiSW), by the National Science Centre grant 2015/17/B/ST2/00101, as well as by PL-Grid Infrastructure.

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