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Theoretical analysis of a possible observation of the chiral magnetic effect in $Au + Au$ collisions

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1 Hadronic background of the CME

The existence of nontrivial topological configurations in the QCD vacuum is a fundamental property of the nonabelian gauge theory. Transitions between topologically different states occur with a change of the topological quantum number n_w characterizing these states and induce anomalous processes like local violation of the $\mathcal{P}$ and $\mathcal{CP}$ symmetry. The idea that non-central heavy-ion collisions may result in such a violation was first postulated over a decade ago in Refs. [1, 2]. The interplay of topological configurations with (chiral) quarks shows the local imbalance of chirality. Such a chiral asymmetry when coupled to a strong magnetic field - as created by colliding nuclei perpendicular to the reaction plane - induces a current of electric charge along the direction of the magnetic field which leads to a separation of oppositely charged particles with respect to the reaction plane. Thus, as argued in Refs. [3–6], the topological effects in QCD might be observed in heavy-ion collisions directly in the presence of very intense external electromagnetic fields due to the "Chiral Magnetic Effect" (CME) as a manifestation of spontaneous violation of the $\mathcal{CP}$ symmetry. Indeed, it was shown that electromagnetic fields of the required strength can be created in relativistic heavy-ion collisions [4, 7]. The first

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experimental evidence for the CME - identified via the charge separation effect with respect to the reaction plane - was measured by the STAR Collaboration at the RHIC in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$ =200 and 62 GeV [8,9].

We study the space-time evolution of relativistic heavy-ion collisions within the Hadron-String-Dynamics (HSD) transport approach [14] which goes beyond the on-shell Boltzmann kinetic equation and in line with the Kadanoff-Baym equation treats the nuclear collisions in terms of quasiparticles with a finite width. The HSD model quite successfully describes many observables in a large range of the collision energies [14,15]. In Ref. [13] this approach was extended to include the dynamical formation of the retarded electromagnetic fields, their evolution during a collision and influence on the quasiparticle dynamics as well as the interplay of the created magnetic and electric fields and back-reaction effects. It was shown that the influence of electromagnetic effects on observables is negligible [13]. So, we start our calculations within the traditional HSD approach [14] without the inclusion of the electromagnetic field.

An experimental signal of the local spontaneous parity violation is a charged particle separation with respect to the reaction plane [16]. It is characterized by the two-body correlator in the azimuthal angles,

$$\langle \cos(\psi_\alpha + \psi_\beta - 2\Psi_{RP}) \rangle, \tag{1}$$

where Ψ_{RP} is the azimuthal angle of the reaction plane defined by the beam axis and the line joining the centers of the colliding nuclei. The averaging in Eq. (1) is carried out over the whole event ensemble. The experimental acceptance $|\eta| < 1$ and $0.15 < p_t < 2$ GeV has been also incorporated in the theoretical calculations. Note that the theoretical reaction plane is fixed exactly by the initial conditions and therefore is not defined by a correlation with a third charged particle as in the experiment [12]. Thus, within HSD we calculate the observable (1) as a function of the impact parameter b or centrality of nuclear collisions to be considered as a background of the CME.

The calculated and measured correlation functions for oppositely and same charged pions are shown in Fig. 1 for the available three BES energies. The case for the top HIC energy $\sqrt{s_{NN}}$ =200 GeV is also presented for comparison.

At the lowest measured energy $\sqrt{s_{NN}}$ =7.7 GeV the results for oppositely and same-charged pions practically coincide and show a large enhancement in very peripheral collisions. The centrality distributions of $\langle \cos(\psi_\alpha + \psi_\beta - 2\Psi_{RP}) \rangle$ are well reproduced by the HSD calculations. The striking result is that the case of $\sqrt{s_{NN}}$ =7.7 GeV drastically differs from $\sqrt{s_{NN}}$ =200 GeV (cf. the right bottom panel in Fig. 1). The picture quantitatively changes only slightly when one proceeds to $\sqrt{s_{NN}}$ =11.5 GeV (see the right top panel in Fig. 1) though the value at the maximum (centrality 70%) decreases by a factor of 3 in the calculations. Experimental points at this large centrality are not available but the 'experimental' trend [12] shown by the dashed lines goes roughly to the same value as at 7.7 GeV. In addition, one may indicate a weak charge separation effect in the data because statistical error bars are very small (less than the symbol size). If one looks now at the results for $\sqrt{s_{NN}}$ =39 GeV, the measured same- and oppositely charged pion lines are clearly separated, being positive for the same-charged and negative for the oppositely charged pions but strongly suppressed. The HSD model is not able to describe this picture: it looks like theoretical same- and oppositely charged pions would mutually interchange their positions. The same situation is observed in the case of $\sqrt{s_{NN}}$ =200 GeV; a small difference is seen in very peripheral collisions: the oppositely charged correlation goes to zero at centrality 70% for $\sqrt{s_{NN}}$ =39 GeV while corresponding data at 200 GeV are not available.

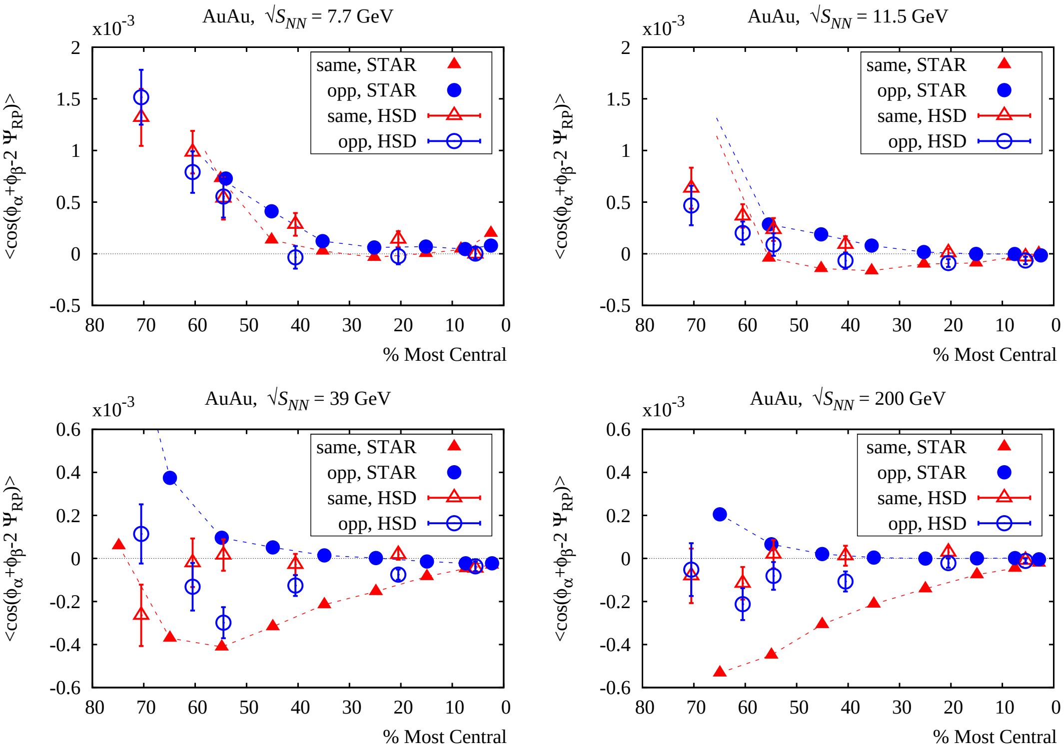

Figure 1: Angular correlations of oppositely and same charged pions in azimuthal angles for Au + Au collisions at $\sqrt{s_{NN}}$ =7.7, 11.5, 39 and 200 GeV as a function of centrality. The full symbols are preliminary STAR data [12] and published STAR data for $\sqrt{s_{NN}}$ = 200 GeV [9]. The dashed lines connect the experimental points (for orientation) as in the experimental works.

Though the results at $\sqrt{s_{NN}}$ =7.7 and 11.5 can be considered as a background of the CME, at higher energies it is impossible to identify the true effect of the local parity violation as the difference between measured and HSD results. The HSD model does not include directly the dynamics of quark-gluon degrees-of-freedom which are getting important with increasing energy. These effects are incorporated in the novel Parton-Hadron-String-Dynamics (PHSD) approach [17] which has not yet been incorporated in the present study for the CME. An increasing importance of a repulsive partonic component is illustrated by a rise of the elliptic flow explained convincingly in the PHSD model [18].

Nevertheless, we want to stress the point that, the two particle correlation (1) can be decomposed in "in-plane" and "out-of-plane" components [1]

$$\begin{aligned} \langle \cos(\phi_\alpha + \phi_\beta) \rangle &= \langle \cos(\phi_\alpha)\cos(\phi_\beta) \rangle \\ &- \langle \sin(\phi_\alpha)\sin(\phi_\beta) \rangle \ . \end{aligned} \tag{2}$$

Following Ref. [10] in Fig. 2 and Fig. 3 these components are presented for the same $(+,+), (-,-)$ and opposite $(+,-)$ charged pion pairs.

Since the observed correlation (2) is the difference of these two terms, the calculated correlation is small as well. Furthermore, for the same charge pairs the measured *sine* term is essentially zero while the *cosine* term is finite. This implies that the observed correlations are

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[1] For brevity, below we shall suppress Ψ in Eq.(1) but the azimuthal angle ϕ should be measured with respect to the reaction plane.

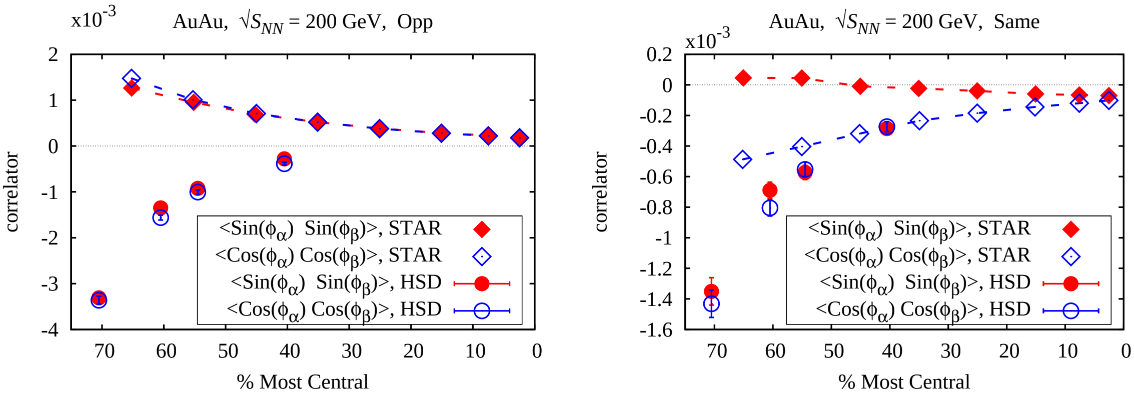

Figure 2: Projections of azimuthal correlations on the in- and out-reaction plane of oppositely and same charged pions in azimuthal angles for $Au+Au$ collisions at $\sqrt{s_{NN}}$ =200 GeV as a function of centrality. The full symbols are published STAR data for $\sqrt{s_{NN}}$ = 200 GeV [9]. The dashed lines connect the experimental points (for orientation) as in the experimental works.

in-plane rather than out-of-plane, as expected. It is of interest that the measured and calculated *cosine* terms coincide with each other for centralities $\lesssim$0.55. As was noted in Ref. [10], the zero *sine* component is contrary to the expectation from the CME, which for the same charge correlation results in an out-of-plane correlation. In the HSD model the *sine* term is not zero but negative. This is not a surprise because the induced chromoelectric field parallel to the out-of-plane B_y is not included into our calculations, but there is a nonzero electric field component E_y (see above). Furthermore, we see that for opposite charge pairs the *sine* and *cosine* correlation terms are virtually identical, which, according to Refs. [10, 11], is hard to reconcile with a sizable elliptic flow in these collisions. However, the centrality distributions of opposite charge pions exhibit contrary trends: the STAR measurement is positive and decreases but the HSD result is negative and increases toward central collisions where all components of angular correlations $\approx$0. It is noteworthy that the UrQMD model shows quite close results. Indeed, $\langle\cos(\phi_\alpha-\phi_\beta)\rangle$ is just the sum of *cosine* and *sine* terms. So, summing the two opposite charge curves in Fig. 2 we reproduce the UrQMD results presented in Fig.5 of Ref. [9].

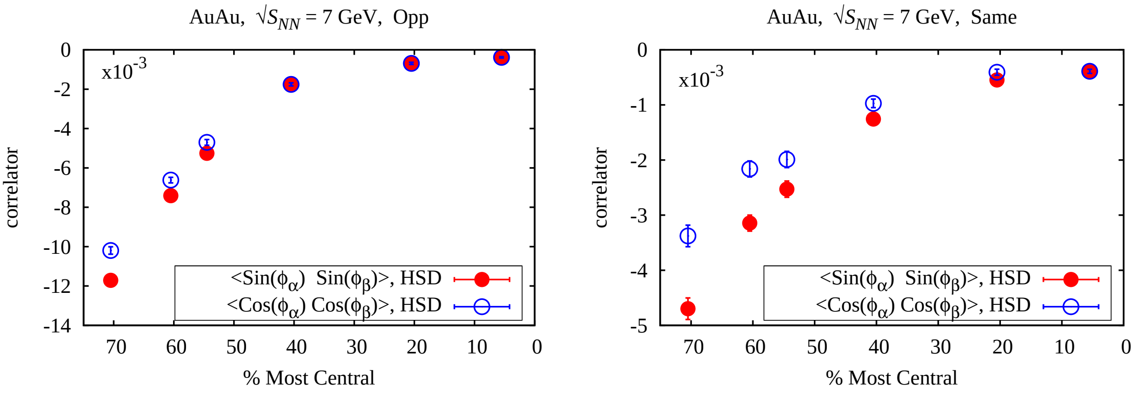

Figure 3: Projections of azimuthal correlations on the in- and out-reaction plane of oppositely and same charged pions in azimuthal angles for $Au+Au$ collisions at $\sqrt{s_{NN}}$ =7 GeV as a function of centrality. Experimental data is unavailable.

The consideration of in-plane and out-of-plane projection components of correlator (1) does not allow us to clarify the picture and rises new questions related to the experiment [10, 11].

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