# Theoretical analysis of a possible observation of the chiral magnetic effect in Au + Au collisions within the RHIC beam energy scan program

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In terms of the hadron-string-dynamics (HSD) approach, we investigate the correlation function in the azimuthal angle $\psi$ of charged hadrons that is expected to be sensitive to a signal of local strong parity violation. Our analysis of Au + Au collisions is based on the recent STAR data within the RHIC beam-energy-scan (BES) program. The HSD model reasonably reproduces STAR data for $\sqrt{s_{NN}}$ =7.7 GeV, while there are some deviations from the experiment at the collision energy of 11.5 GeV and an increase of deviations between theory and experiment at $\sqrt{s_{NN}} = 39$ GeV. For reference, the results for $\sqrt{s_{NN}} = 200$ GeV are given as well. The role of the retarded electromagnetic field is discussed and a compensation effect for the action of its electric and magnetic components is pointed out. We conclude that the recent RHIC BES data at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV can be understood on the hadronic level without involving the idea of a strong parity violation; however, the HSD model fails to reproduce data for $\sqrt{s_{NN}} \sim 40$ GeV and above which suggests that at these energies one has to take into account explicit partonic (quark-qluon) degrees of freedom for a proper treatment of the dynamics as well as a coupling of the partons to fluctuating color fields.

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## I. INTRODUCTION

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 noncentral 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 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].

These results from the STAR Collaboration on charge-dependent correlations are consistent with theoretical expectations for the CME. Accordingly, a positive correlation for like-sign charged pion pairs and a negative one for unlike-sign charged pairs was observed, but these correlations might have contributions from other effects that prevent a definitive interpretation of the data. This finding has been a subject of intense discussions for the last few years. The search for different sources of the background and additional manifestations of local parity violation has been discussed in Refs. [10–14]). Several of these contaminating sources have been investigated, but none was found to consistently create signals of the right magnitude and centrality dependence. It turned out to be possible to reproduce the observed charge asymmetry at both energies of $\sqrt{s_{NN}} = 62$ and 200 GeV in terms of a simple phenomenological model in Ref. [15]. This model considers a one-dimensional random walk in the topological quantum number space within a background magnetic field calculated dynamically within the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model. The topological charge $n_w$ generated during the lifetime $\tau_B$, when the magnetic field is present, can be related to the measured angular correlator by tuning $\tau_B$ at a single energy at the given centrality. The model nicely reproduces the STAR results at both energies and predicts that the CME should disappear below the collision energy close to the top CERN Super Proton Synchrotron (SPS) energy of $\sqrt{s_{NN}} \sim 20$ GeV [15].

Recently, preliminary data below the nominal RHIC energy within the RHIC beam-energy-scan (BES) program have been obtained [16]. In our work we analyze these data to clarify to which extent they might be related to the CME. Our consideration is based on the hadron-string-dynamics (HSD) approach that has been employed before in our study of the CME at the top RHIC energy [17]. The role of the retarded electro-magnetic fields generated during the nuclear collision and, in particular, the impact of electric and magnetic transverse components will be discussed in detail.

## II. HADRONIC BACKGROUND OF THE CME

We study the space-time evolution of relativistic heavy-ion collisions within the HSD transport approach [18] which goes beyond the on-shell Boltzmann kinetic equation and in line with the Kadanoff-Baym equation that 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 [18,19]. In Ref. [17] 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 at the collision energy $\sqrt{s_{NN}} = 200$ GeV [17]. So, we start our calculations within the traditional HSD approach [18] without the inclusion of the electromagnetic field and come back to this issue in the next section.

An experimental signal of the local spontaneous parity violation is a charged particle separation with respect to the reaction plane [20]. 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 $\Psi_{RP}$ 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 [16]. 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. The statistics of the calculated events is given in Table I.

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 [16] 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.

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 [21] 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 [22].

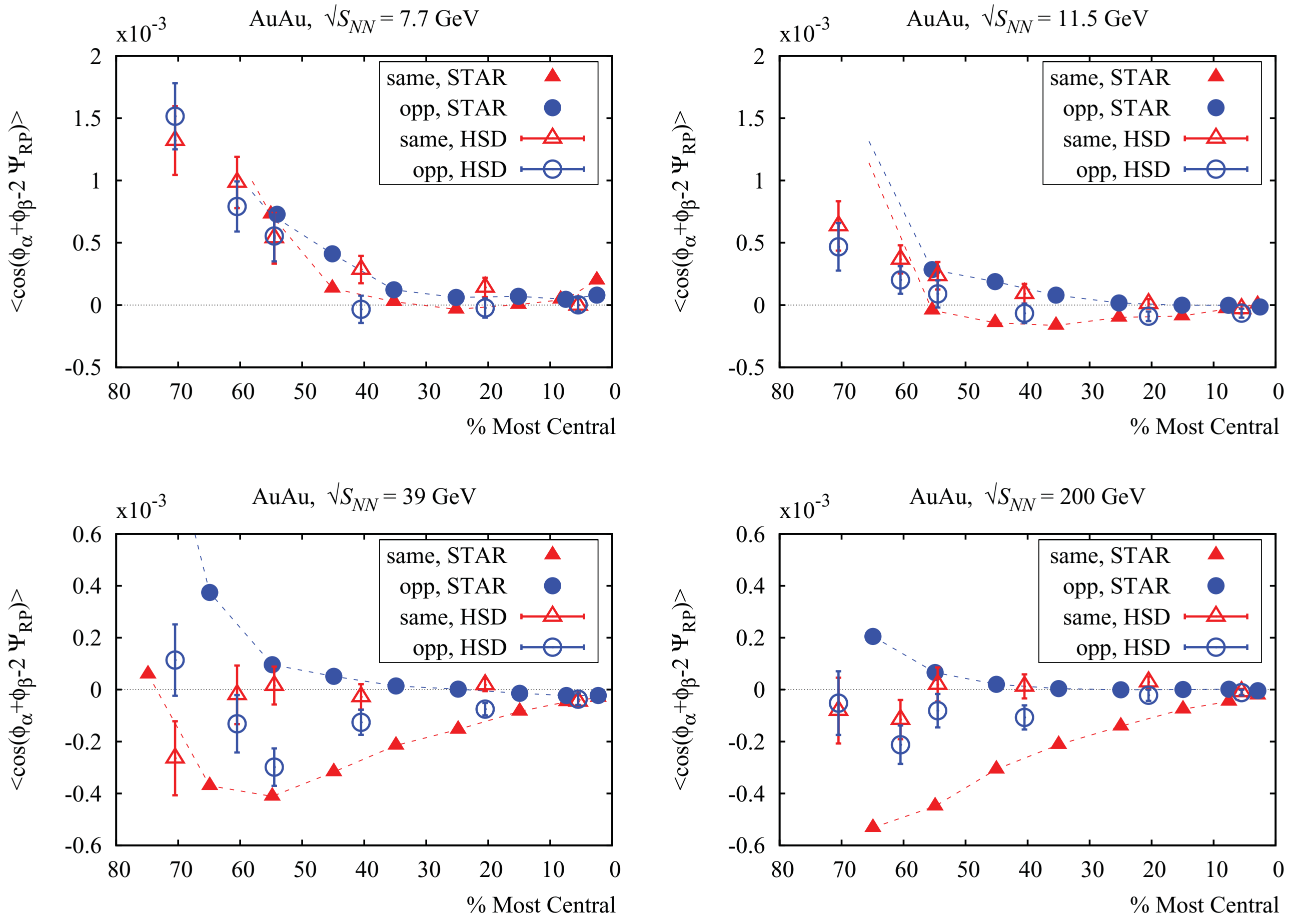


FIG. 1. (Color online) Angular correlations of oppositely and same-charged pions in azimuthal angles for Au + Au collisions at $\sqrt{s_{NN}} =$ 7.7, 11.5, 39, and 200 GeV as a function of centrality. The full symbols are preliminary STAR data [16] and published STAR data for $\sqrt{s_{NN}} = 200$ GeV [9]. The dashed lines connect the experimental points (for orientation) as in the experimental works.

Thus, azimuthal correlations at the energies $\sqrt{s_{NN}} =$ 7.7 and 11.5 GeV are quite reasonably reproduced by the hadronic dynamics within the HSD model leaving no room for further effects of local parity violation. The situation at higher collision energies is more complicated and uncertain. Evidently other sources of correlations cannot be excluded for $\sqrt{s_{NN}} \gtrsim 40$ GeV. In this energy range quark-gluon degrees of freedom became essential as well as fluctuations of the color fields. In this respect an application of the PHSD approach [21] will be mandatory on an event-by-event basis incorporating the fluctuations of the partonic mean fields.

TABLE I. Statistics of calculated Au + Au collision events in the HSD model (in $10^3$).

| Centrality (%) | 200 GeV | 39 GeV | 11.5 GeV | 7.7 GeV |
|---|---|---|---|---|
| 70 | 400 | 600 | 600 | 600 |
| 60 | 200 | 200 | 400 | 200 |
| 55 | 100 | 200 | 200 | 100 |
| 40 | 20 | 40 | 40 | 40 |
| 20 | 15 | 20 | 20 | 10 |
| 5 | 3 | 5 | 5 | 5 |

## III. EFFECTS OF THE RETARDED ELECTROMAGNETIC FIELD

We have mentioned above that the HSD model has been extended to take simultaneously into account the creation and evolution of retarded electromagnetic fields treated by the Maxwell equations in the vacuum [17] and their back reaction on the particle propagation.

As was pointed out in Ref. [23], fluctuations in initial proton positions may result in high fluctuations of electromagnetic fields. In Ref. [23] this was demonstrated in terms of a rather schematic model at time $t = 0$ and at the single point $\vec{x} = 0$. The HSD calculations are performed on an event-by-event basis, and therefore dynamical fluctuations in the hadronic variables (including initial nucleon positions) are included. However, the retarded electromagnetic fields are calculated by averaging over events in a parallel ensemble. Thus, electromagnetic field fluctuations due to initial proton position fluctuations are averaged out in the present study. Unfortunately, our analysis has shown that the bulk observables and

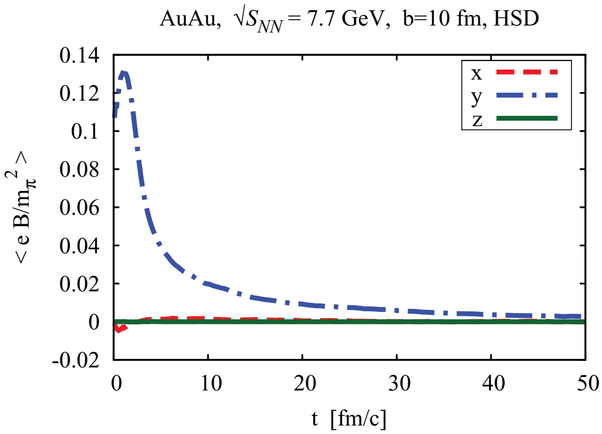


FIG. 2. (Color online) Time dependence of the average magnetic $\vec{B}$ and electric $\vec{E}$ fields acting on forward-flying positively charged mesons created at the time $t$ in peripheral ($b = 10$ fm) Au + Au ($\sqrt{s_{NN}} = 7.7$ GeV) collisions.

charge separation effect are not sensitive to the electromagnetic field dynamics at $\sqrt{s_{NN}} = 200$ GeV [17].

From Fig. 2 one may get an idea about the strength of the magnetic and electric field in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV in a peripheral reaction with the impact parameter $b = 10$ fm. The magnetic field is perpendicular to the reaction plane $(x, z)$, and it's maximal value is about $0.13 m_\pi^2$ which is by about an order of magnitude lower than at $\sqrt{s_{NN}} = 200$ GeV (cf. [17]). This is still a rather strong magnetic field, and it persists by about a factor of 20 times longer than that

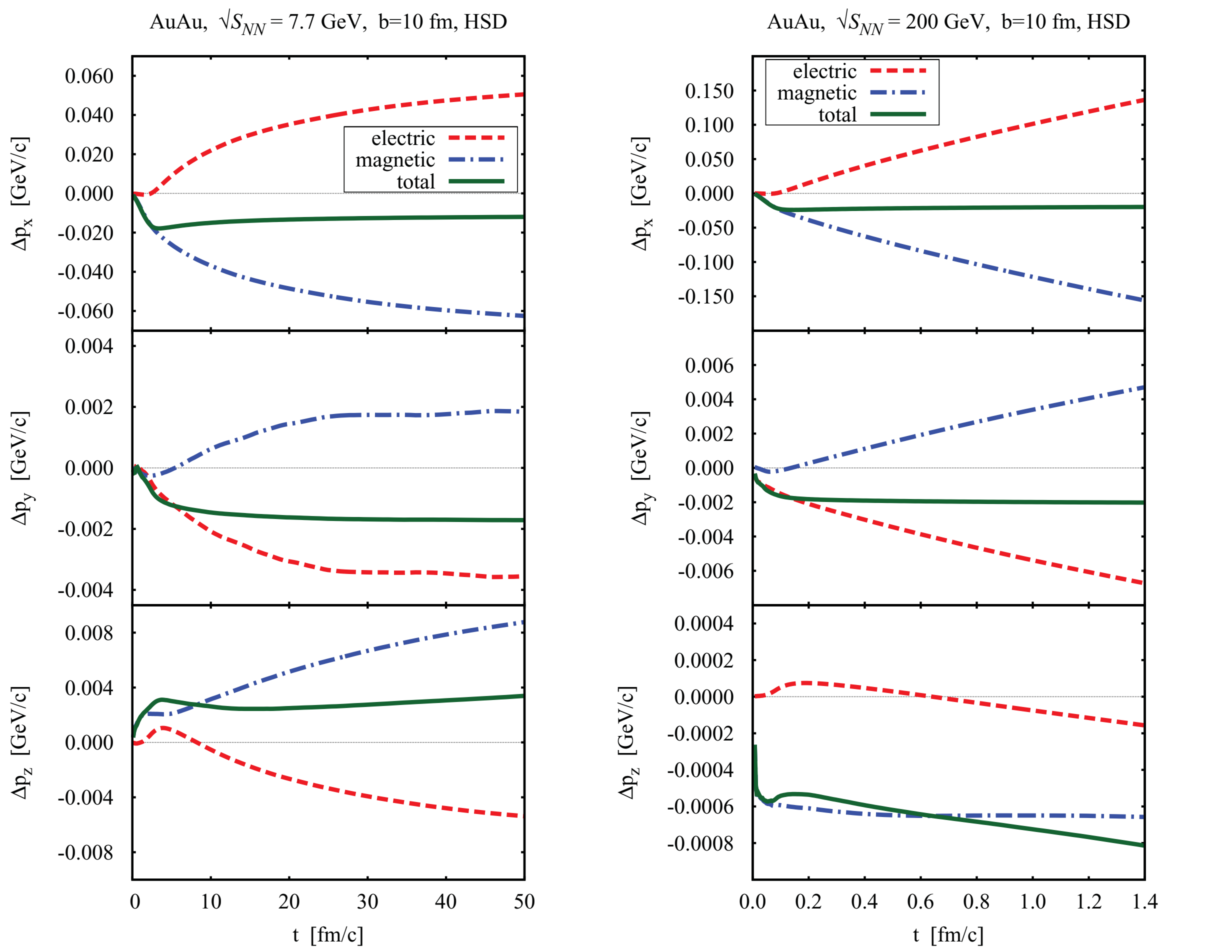


FIG. 3. (Color online) Time dependence of the momentum increment $\Delta\vec{p}$ of forward-flying positively charged poins created in Au + Au at $\sqrt{s_{NN}} = 7.7$ (left panel) and 200 (right panel) GeV collisions for the impact parameter $b = 10$ fm within the HSD model.

at $\sqrt{s_{NN}} = 200$ GeV. The electric field, oriented essentially along the $x$ axis, is also sizable and decreases in time somewhat slower than the magnetic field.

Naively, one might think that the insensitivity of observables to the electromagnetic field created in relativistic nuclear collisions is due to the short interaction time when the created field has its maximum. However, this is not the case. Let us look at the early time dynamics in more detail and introduce a momentum increment $\Delta\vec{p}$ as a sum of the average increase of the particle momentum $d\vec{p}$ due to the action of the electric and magnetic forces, $e\vec{E} + (e/c)\vec{v} \times \vec{B}$, on pions during the short time interval at the expense of the given source:

$$\Delta\vec{p} = \sum_{t_i} \langle d\vec{p}(t_i)\rangle. \tag{2}$$

In Fig. 3 the average momentum change of positive pions is shown for the three components of the electromagnetic force at two collision energies. Note the different time scale at these energies and that the increment components are noticeably larger for the top RHIC energy. It is a remarkable fact that in both cases the transverse electric and magnetic components are almost completely compensated (solid lines in Fig. 3). For a quasiparticle at $x = x(t)$ in a simplified one-dimensional (1D) case, this compensation can be illustrated by a short calculation as

$$eE = -e\frac{\partial A}{\partial t} \sim -e\frac{\partial A}{\partial x}\frac{dx}{dt} \sim -eBv, \tag{3}$$

i.e., the action of the electric and magnetic transverse components is roughly equal and inversely directed. This finding illustrates that considerations of heavy-ion collisions with only magnetic fields are not appropriate and misleading.

## IV. SUMMARY AND OUTLOOK

Our study shows that the two-pion azimuthal angular correlations—as measured by the STAR Collaboration—and considered as a possible signal of local parity violation in strong interactions can be reasonably described at moderate energies $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV within the conventional microscopic transport HSD model. The observed behavior of oppositely and same-sign charged pions is correctly reproduced in shape and roughly in absolute magnitude without involving the parity violation concept. This finding is in agreement with the prediction that the CME will not be observable at energies below the top SPS energy, $\sqrt{s_{NN}} \lesssim 20$ GeV [15]. Indeed, the situation is very different at higher energies $\sqrt{s_{NN}} = 39$ GeV and consistent with the findings at the top RHIC energy $\sqrt{s_{NN}} = 200$ GeV. The calculated hadronic background is definitely not sufficient to explain the experimental observations though hadronic competing effects as considered in Refs. [10–12,14] which are involved to a large extent. Nevertheless, other sources for pion correlations—stemming from explicit partonic dynamics and color field fluctuations—have to be considered as well in the future. A simulation of the genuine CME is of great interest; however, a simultaneous analysis of all other hadronic observables will be very important to restrict the models of relevance to this issue.

We have found out that the average of retarded strong electromagnetic fields created during nucleus-nucleus collisions turns out to be not so important as expected before. The electromagnetic field has almost no influence on hadronic observables and, in particular, on the asymmetry of charged mesons with respect to the reaction plane [17]. The reason is not a shortness of the interaction time, when the electromagnetic field is maximal, but the demonstrated compensation of the mutual action of transverse electric and magnetic components. This compensation effect may be important, for example, if an additional induced electric field (as a source of the CME) is available in the system since this field will not be entangled due to other electromagnetic sources.

Another important point emerging from the compensation effect is the following: A significance of an external magnetic field in astrophysics is largely accepted. There are many studies where various effects of external magnetic fields are discussed in application to astrophysics (e.g., see the Introduction in Ref. [17] and references in [24]). This is correct in the particular problems considered; however, in many cases it is concluded by statements like "the same effect should be observed in high-energy heavy-ion collisions" which does not hold true due the compensation effect as demonstrated in the present work.

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