# HAVE WE SEEN LOCAL PARITY VIOLATION IN HEAVY-ION COLLISIONS?*

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In this contribution we will discuss current measurements of charge dependent particle correlations and their implication for possible local parity violation.

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## 1. Introduction

Topological objects in Quantum Chromodynamics (QCD) (and generally in non-Abelian gauge theories) have attracted persistent theoretical interests and are important in many aspects [1]. For example, instantons are known to be responsible for various properties of the QCD vacuum, such as spontaneous breaking of chiral symmetry and the $U_A(1)$ anomaly (see *e.g.* [2, 3]). Magnetic monopoles, on the other hand, are speculated to be present in the QCD vacuum in a Bose-condensed form which then enforce the color confinement, known as the dual superconductor scenario for QCD confinement which is strongly supported by evidences from lattice QCD (see *e.g.* [4, 5]). Alternatively, vortices are also believed to describe the chromo-electric flux configuration (*i.e.* flux tube) between a quark–antiquark pair in the QCD vacuum which in turn gives rise to the confining linear potential (see *e.g.* reviews in [5, 6]). Some of these objects, such as monopoles [7] and flux tubes [8], may also be important degrees of freedom in the hot and deconfined QCD matter close to the transition temperature $T_c$, and may be responsible for the observed properties of the so-called strongly

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coupled quark-gluon plasma [9]. Certain phenomenological consequences of such topological objects for relativistic heavy ion collisions have been studied in [10].

A particularly interesting suggestion by Kharzeev and collaborators [11, 12, 13, 14, 15, 16] on the direct manifestation of effects from topological objects is the possible occurrence of $\mathcal{P}$- and $\mathcal{CP}$-odd (local) domains due to the so-called sphaleron transitions in the hot dense QCD matter created in the relativistic heavy ion collisions. In particular, the so-called Chiral Magnetic Effect (CME) [13] predicts that in the presences of the strong external (electrodynamic) magnetic field at the early stage after a (non-central) collision sphaleron transitions induce a separation of charges along the direction of the magnetic field. Since the external magnetic field is perpendicular to the reaction plane[1] defined by the impact parameter and the beam axis, one expects an out-of-plane charge separation. As a result, positive charges are expected to preferentially go in one (out-of-plane) direction and negative charges in the opposite (out-of-plane) direction. As depicted in Fig. 1, in a given event, this charge separation results in a momentum space electric dipole which breaks parity. However, the dipole moment will be, with equal probability, parallel or anti-parallel to the magnetic field depending whether the Chiral Magnetic Effect is caused by a sphaleron or anti-sphaleron transition. Consequently, the expectation value of the dipole or, more precisely, of the scalar product of the dipole and the magnetic field, will vanish.

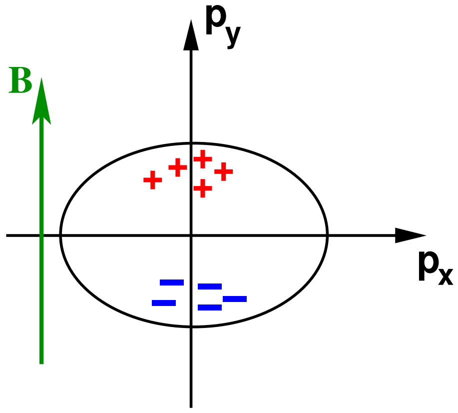


Fig. 1. A schematic illustration of charge separation due to the Chiral Magnetic Effect in an heavy ion event. The reaction plane is aligned along the $p_x$-direction in this case.

[1] As shown recently in [17] fluctuating proton positions generate equally strong magnetic (and electric) fields also in the direction parallel to the reaction plane.

For the aforementioned reasons the CME will *not* give rise to a non-vanishing expectation value of a $\mathcal{P}$-odd observable. However, the fact that parity is broken event-by-event should be reflected in the variance of a $\mathcal{P}$-odd observable, and the event-by-event charge separation should be observable in a suitable correlation measurement. Such a measurement has been proposed by Voloshin in [18] and recently carried out by the STAR Collaboration [19, 20]. Here we will discuss to which extent the STAR measurement is indeed sensitive to the CME. Details can be found in [21, 22, 23].

## 2. Correlations and the CME

As briefly discussed in the introduction, the Chiral Magnetic Effect leads to the separation of charges along the direction of the magnetic field generated by the moving ions, which can be viewed as a dipole in momentum space (see Fig. 1). Since in a given event the dipole vector will be either parallel or anti-parallel to the magnetic field, the expectation value of the momentum-space dipole-moment vanishes, $\langle \vec{d} \rangle = 0$, as does the expectation value of the parity-odd scalar product with the magnetic field, $\langle \vec{B}\vec{d} \rangle = 0$. However, since $\langle \vec{d}^2 \rangle \neq 0$, the variance of the event-by-event electric dipole may be observable in the *variance* of a parity-odd operator, or equivalently, in charge-dependent two-particle correlations. Of course, simple statistical fluctuations also give rise to a finite $\langle \vec{d}^2 \rangle$ and suitable observables have to be devised which are not sensitive to these statistical fluctuations (for a discussion see [22]).

One way to obtain information about the presences of the CME is to study charge dependent two-particle correlations with respect to the reaction plane, as proposed by Voloshin [18]. He suggested to measure the following three-particle correlation

$$\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle \tag{1}$$

for same-charge pairs $(i, j = ++/--)$ and opposite-charge pairs $(i, j = +-)$ with the third particle, denoted by index $k$, having any charge. If the correlation with the third particle $k$ is dominated by elliptic flow, then

$$\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle = v_2 \langle \cos(\phi_i + \phi_j - 2\Psi_{\mathrm{RP}}) \rangle \,, \tag{2}$$

where $\Psi_{\mathrm{RP}}$ is the angle of the reaction plane, and $v_2$ denotes the strength of the elliptic flow. Working in a frame where the reaction plane is along the $x$-axis, $\Psi_{\mathrm{RP}} = 0$, we get

$$\gamma \equiv \frac{1}{v_2} \langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle = \langle \cos(\phi_i + \phi_j) \rangle \,. \tag{3}$$

The STAR Collaboration has recently measured this correlator and indeed has verified the above dependence on the elliptic flow. Before we discuss the STAR measurement in detail, however, let us see what to expect for this observable in the case of CME. As can be seen from Fig. 1, the CME predicts same-side out-of-plane correlations for same-charges and back-to-back out-of-plane correlations for opposite-charges. This is best seen by rewriting the correlator $\gamma$ as

$$\gamma = \langle \cos(\phi_i + \phi_j) \rangle \ = \ \langle \cos(\phi_i) \cos(\phi_j) \rangle - \langle \sin(\phi_i) \sin(\phi_j) \rangle \,. \qquad (4)$$

In this representation the first term, $\langle \cos(\phi_i) \cos(\phi_j) \rangle$, measures the in-plane correlations while the second term, $\langle \sin(\phi_i) \sin(\phi_j) \rangle$, measures the out-of-plane correlations. The CME predicts that same-charge pairs have either both an angle of $\phi_i, \phi_j \simeq \pi/2$ or $\phi_i, \phi_j \simeq 3\pi/2$. In either case, $\sin(\phi_i) \sin(\phi_j) \simeq 1$. For opposite-charges, $\phi_i \simeq \pi/2$; $\phi_j \simeq 3\pi/2$ or *vice versa* and $\sin(\phi_i) \sin(\phi_j) \simeq -1$. Hence the CME predicts

$$\begin{aligned} \gamma_{\mathrm{CME,\,same-charge}} &< 0\,, \\ \gamma_{\mathrm{CME,\,opposite-charge}} &> 0\,, \end{aligned} \qquad (5)$$

and indeed this is what the STAR measurement shows. So have we seen the CME and thus local parity violation in an actual experiment? Not quite yet, because there is an alternative scenario for which the correlator $\gamma$ may be negative for same-charge pairs and positive for opposite-charge pairs: Suppose we have same-charge *in-plane* back–back correlations, *i.e.* $\phi_i \simeq 0$ and $\phi_j \simeq \pi$ or *vice verse*, and opposite-charge *in-plane* same-side correlations, *i.e.* $\phi_i, \phi_j \simeq 0$ or $\phi_i, \phi_j \simeq \pi$ we obtain the same signs for $\gamma$ as above, but this time it is the $\langle \cos(\phi_i) \cos(\phi_j) \rangle$ term which controls things. In other words, the correlator $\gamma$ is not unique and we need another observable to determine whether we are actually observing in-plane or out-of-plane correlations. The obvious candidate is

$$\delta \equiv \langle \cos(\phi_i - \phi_j) \rangle \ = \ \langle \cos(\phi_i) \cos(\phi_j) \rangle + \langle \sin(\phi_i) \sin(\phi_j) \rangle \qquad (6)$$

which represents the *sum* of the in-plane ($\langle \cos(\phi_i) \cos(\phi_j) \rangle$) and out-of-plane ($\langle \sin(\phi_i) \sin(\phi_j) \rangle$) correlations. With both $\gamma$ and $\delta$ we can extract both in-plane and out-of-plane correlations separately

$$\begin{aligned} \langle \cos(\phi_i) \cos(\phi_j) \rangle &= \tfrac{1}{2}(\delta + \gamma) \ \ \text{(in-plane)}\,, \\ \langle \sin(\phi_i) \sin(\phi_j) \rangle &= \tfrac{1}{2}(\delta - \gamma) \ \ \text{(out-of-plane)}\,. \end{aligned} \qquad (7)$$

Fortunately, STAR has measured the correlator $\delta$ allowing for a decomposition of the in-plane and out-of-plane correlations. Those are shown in Fig. 2 for same-charge pairs and in Fig. 3 for opposite-charge pairs. The surprising result is that for same-charge pairs the measured out-of-plane correlations are essentially zero, in contrast to the predictions from the CME. Instead STAR observes an *in-plane* back-to-back correlation! This situation is illustrated in Fig. 4. Opposite-charge pairs, on the other hand, seem to be

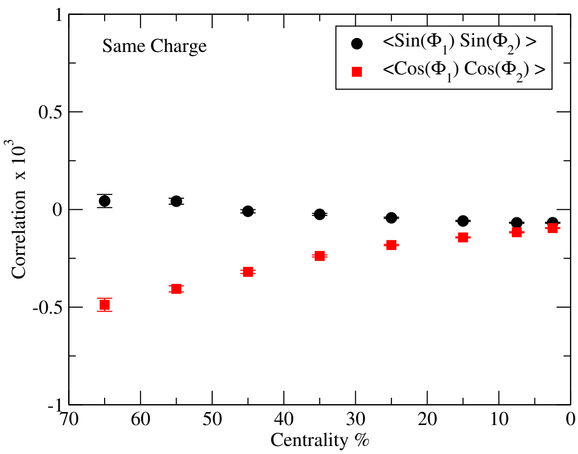


Fig. 2. In-plane (squares/red) and out-of-plane (circles/black) correlations for same-charge pairs as measured by the STAR Collaboration [19, 20]. For details see [21].

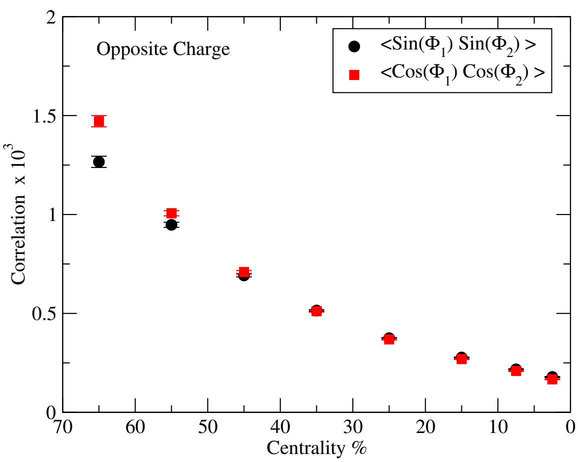


Fig. 3. In-plane (squares/red) and out-of-plane (circles/black) correlations for opposite-charge pairs as measured by the STAR Collaboration [19, 20]. For details see [21].

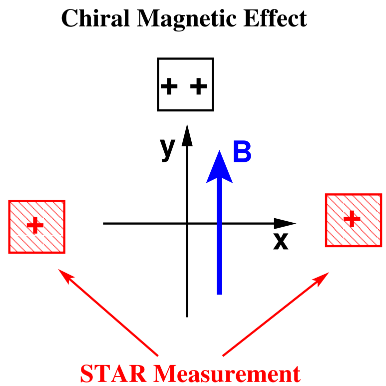


Fig. 4. Schematic illustration of the actual STAR measurement (hatched, red) together with the predictions from the Chiral Magnetic Effect (black) for same-charge pairs.

equally correlated in both the in-plane and out-of-plane direction. Obviously, this is not quite in agreement with the expectation from the CME. Especially the fact that the same-charge pairs do not show any out-of-plane correlations for all centralities is difficult to understand in the context of the CME predictions. Naturally, there will be other effects contributing to the correlators $\gamma$ and $\delta$, such as the Coulomb interaction, transverse-momentum conservation [23], local charge conservation [24, 25], cluster-decays [26] *etc.* However, it is difficult to imagine how for all centralities these "background" contributions conspire to perfectly cancel the correlations expected from the CME. One should note, however, that so far the measured correlations are not understood in terms of conventional physics either, possibly because many effects contribute, as indicated above. Recently, the ALICE Collaboration has reported preliminary results on the measurement of same correlation functions at LHC energies. While the correlator $\gamma$ is essentially the same as the one measured by STAR, the two particle correlation $\delta$ measured by ALICE is positive for both like and unlike sign pairs [29]. As a consequence, at LHC energies there appears to be a significant out-of-plane component of the same-sign correlation, in agreement with expectation from the CME. However, in order to draw more definitive conclusions, it would be very useful to have a more differential information on the above correlations. While STAR has extracted the rapidity and transverse-momentum dependence of $\gamma$ this information is not yet available for $\delta$. In addition, the value for the above correlations in simple proton–proton collisions would serve as an important reference point.

It may also be useful to develop alternative observables [22, 27]. For example in [22] the direct extraction of the magnitude and direction with respect to the reaction plane of the momentum-space dipole-moment has been proposed by introducing a charge-dependent $Q$-vector analysis [28]. In [22], it was also demonstrated that simple two-particle correlations may mimic the effect of an actual dipole, and only the careful analysis of the distributions of both the magnitude and the angle of the extracted dipole would be able to distinguish between an explicit dipole and other correlations.

## 3. Conclusions

In this contribution, we have critically examined the STAR measurements of charge dependent two and three particle correlations and their relevance for local parity violation. We found that for same-charge pairs the STAR data shows the in-plane back-to-back correlations in contradistinction to the prediction from the Chiral Magnetic Effect, which predicts out-of-plane same-side correlations. This picture changes when going to LHC energies, where preliminary data from the ALICE Collaboration are consistent with a significant out-of-plane same-side correlations of like sign pairs. Therefore, the jury on the existence of local parity violation in heavy ion collision is still out.

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