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Permalink

<https://escholarship.org/uc/item/23s8w049>

Journal

European Physical Journal A, 52(8)

ISSN

1434-6001

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Publication Date

2016-08-01

DOI

10.1140/epja/i2016-16265-0

Peer reviewed

Particle Correlations and the Chiral Magnetic Effect

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the date of receipt and acceptance should be inserted later

Abstract. In this contribution we will discuss current measurements of particle correlations and their implication for possible local parity violation in heavy-ion collisions.

PACS. 25.75.-q Relativistic heavy-ion collisions – 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries

1 Introduction

Experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have triggered quite a number of interesting fundamental questions to our understanding of strongly interacting matter under extreme conditions. Among them is that of a possible detection of local parity violation due to the non-trivial topological properties of QCD. In the context of heavy ion collisions locally nonzero topological charge densities (aka nonzero chromo $\mathbf{E}^a \cdot \mathbf{B}^a$) naturally occur, both via sphaleron transitions and by virtue of the glasma chromo-flux tubes, thus creating a local $\mathcal{P}$ - and $\mathcal{CP}$ -odd environment. For a chirally restored phase created in heavy ion collisions, such topological charge densities couple to light quarks through chiral anomaly and “translate” into an *imbalance* between right-handed (RH) and left-handed (LH) quarks. It is widely believed that heavy ion collisions at RHIC and LHC energies produce systems which are deep in the Quark Gluon Plasma phase, and thus chiral symmetry is restored. At lower energies, such as those expected to be available at NICA and FAIR, one expects that the produced fireball will not only have a considerable net baryon density but will also be rather close to the chiral restoration transition. Therefore, the determination of the beam energy dependence of the observables associated with possible local parity violation will be essential to find the chiral phase transition.

It was suggested by Kharzeev and collaborators that such a chiral QGP with RH/LH imbalance could be created in heavy ion collisions and result in the so-called Chiral Magnetic Effect (CME) [1]. The Chiral Magnetic Effect predicts that in the presence of the strong external (electrodynamical) magnetic field at the early stage af-

ter a (non-central) collision, the chirality imbalance of the quark sector induces a separation of charges along the direction of the magnetic field (which is approximately along the out-of-plane direction). Of course, sphaleron and anti-sphaleron transitions, and the resulting positive/negative chirality imbalance, are equally likely. Therefore, the event-averaged charge separation will vanish. However, if present, the event-by-event charge separation should be observable in a suitable correlation measurement. Such a measurement has been proposed by Voloshin in [2] and carried out initially by the STAR collaboration [3,4]. A lot of subsequent measurements were further done by STAR [5,6,7,8] as well as by other collaborations [9,10]. For reviews and references on this subject, see e.g., [11,12,13].

In this contribution we will focus on a number of important issues in the search of CME: to which extent the present STAR measurements are sensitive to the CME, what backgrounds need to be considered, and how to minimize these backgrounds to extract possible CME signals. Details can be found in [14,15,16,11]

2 Local parity violation in heavy ion collisions?

As briefly discussed in the Introduction, the Chiral Magnetic Effect (CME) leads to the separation of charges along the direction of the magnetic field generated by the moving ions. This charge separation can be viewed as a dipole in momentum space as depicted in Fig. 1. In case of the CME, in a given event the dipole vector will be either parallel or anti-parallel to the magnetic field, depending on the presence of sphaleron- or anti-sphaleron transitions in the reaction. Therefore, the expectation value of

the momentum-space dipole-moment vanishes, $\langle \mathbf{d} \rangle = 0$, as does the expectation value of the parity-odd scalar product with the magnetic field, $\langle \mathbf{B} \cdot \mathbf{d} \rangle = 0$. However, since $\langle \mathbf{d}^2 \rangle \neq 0$ the presence of an 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 $\langle \mathbf{d}^2 \rangle$ and suitable observables have to be devised which are not sensitive to these statistical fluctuations (for a detailed discussion see [15]).

One way to obtain information about the presence of the CME is to study charge dependent two-particle correlations with respect to the reaction plane, as proposed by Voloshin [2]. He suggested to measure the following three-particle correlation,

$$\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle \quad (1)$$

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

$$\langle \cos(\phi_i + \phi_j - 2\phi_k) \rangle = v_2 \langle \cos(\phi_i + \phi_j - 2\Psi_{R.P.}) \rangle \quad (2)$$

where $\Psi_{R.P.}$ 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, $\Psi_{R.P.} = 0$, we get

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

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

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 case of the 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 γ as

$$\gamma = \langle \cos(\phi_i + \phi_j) \rangle = \langle \cos(\phi_i) \cos(\phi_j) \rangle - \langle \sin(\phi_i) \sin(\phi_j) \rangle \quad (4)$$

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 ϕ_i, ϕ_j preferably in the range $(0, \pi)$ or in the range $(\pi, 2\pi)$. In either case, $\sin(\phi_i) \sin(\phi_j) > 0$. For opposite charges, $\phi_i \in (0, \pi)$; $\phi_j \in (\pi, 2\pi)$ or vice versa and $\sin(\phi_i) \sin(\phi_j) < 0$. In addition, the CME makes no contribution to the in-plane correlations, i.e. $\langle \cos(\phi_i) \cos(\phi_j) \rangle_{CME} \simeq 0$ for both same and opposite charges. Hence the CME *alone* would predict

$$\begin{aligned} \gamma_{CME, \text{same-charge}} &\simeq -\langle \sin(\phi_i) \sin(\phi_j) \rangle_{CME} < 0 \\ \gamma_{CME, \text{opposite-charge}} &\simeq -\langle \sin(\phi_i) \sin(\phi_j) \rangle_{CME} > 0, \end{aligned} \quad (5)$$

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! The problem is that the correlator γ is ambiguous, as can be easily seen from its definition, Eq. (3). For example $\cos(\phi_1 + \phi_2) = -1$ for both $(\phi_1, \phi_2) = (\pi/2, \pi/2)$ and $(\phi_1, \phi_2) = (0, \pi)$. In other words, the correlator γ *cannot* distinguish between out-of-plane same-side correlations (black plus-signs in Fig. 4) and in-plane back-to-back correlations (red plus signs in Fig. 4). Consequently the STAR measurement is also consistent with same-charge *in-plane* back-to-back correlations, and opposite-charge *in-plane* same-side correlations. Obviously, we need another observable to break this ambiguity. The obvious candidate is

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

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 γ and δ we can extract both in-plane and out-of-plane correlations separately

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

Fortunately, STAR has measured the correlator δ 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 nearly an order of magnitude smaller than the γ correlator, in contrast to the predictions from the CME pattern in Eq.(5). Instead STAR observes an *in-plane* back-to-back correlation pattern that

Fig. 2. In-plane (red) and out-of-plane (black) correlations for same-charge pairs as measured by the STAR collaboration [3, 4]. For details see [14].

Fig. 3. In-plane (red) and out-of-plane (black) correlations for opposite-charge pairs as measured by the STAR collaboration [3, 4]. For details see [14].

dominates the γ correlator! This situation is illustrated in Fig. 4. Opposite-charge pairs, on the other hand seem to be almost 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 show negligibly small correlation strength as compared with the in-plane correlations for all centralities, is difficult to understand in the context of the CME-alone predictions. There are, of course other effects contributing to the correlators γ and δ , such as the coulomb interaction, transverse-momentum conservation [16], local charge conservation [17, 18], cluster-decays [19] etc. It is, however, a highly nontrivial challenge to quantitatively explain why for all centralities these “background” contributions conspire to nearly perfectly cancel the correlations expected from the CME. Since, so far no explanation of the observed correlation structure in terms of conventional physics has been offered either, it is best to keep an open mind and try to further isolate the signal from the background. To this end it is useful to look at these correlation functions in more detail.

Chiral Magnetic Effect

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

3 The influence of elliptic flow on the correlation functions γ and δ

As discussed in the previous sections the Chiral Magnetic Effect (CME) - if it exists - contributes to the reaction plane dependent two-particle correlator γ . However, so do other correlations, and, as we shall discuss, due to the presence of elliptic flow, virtually any two particle correlation will also contribute to γ .

This can be easily seen from the decomposition of γ into in-plane and out-of-plane projections, Eq. (4). For example, consider the extreme, though unrealistic, situation where all particles are produced exactly in-plane. In this case $\langle \sin(\phi_1) \sin(\phi_2) \rangle = 0$ simply because there are no particles in the out-of-plane direction. Obviously in this case, the presence of any two-particle angular correlation mechanism will result in a non-zero value of γ with $\gamma \sim \langle \cos(\phi_1) \cos(\phi_2) \rangle$ arising from in-plane correlations.

To make this more quantitative, let us write down some general relations between the the correlation functions γ and δ

3.1 General relations

In the following we will always work in a frame where the reaction plane angle is set to zero, $\Psi_{RP} = 0$. This means in an experiment, the azimuthal angles in each event need to be appropriately rotated before taking any event averages. Given this so called intrinsic frame, the two-particle correlators γ and δ are given by (see Ref. [20] for more details)

$$\gamma = \frac{\int \rho_2(\phi_1, \phi_2, x_1, x_2) \cos(\phi_1 + \phi_2) d\phi_1 d\phi_2 dx_1 dx_2}{\int \rho_2(\phi_1, \phi_2, x_1, x_2) d\phi_1 d\phi_2 dx_1 dx_2},$$

$$\delta = \frac{\int \rho_2(\phi_1, \phi_2, x_1, x_2) \cos(\phi_1 - \phi_2) d\phi_1 d\phi_2 dx_1 dx_2}{\int \rho_2(\phi_1, \phi_2, x_1, x_2) d\phi_1 d\phi_2 dx_1 dx_2}, \quad (8)$$

where, x denotes all non-essential kinematic variables, $x = (p_t, \eta)$ and $dx = p_t dp_t d\eta$. Here p_t is the absolute value of transverse-momentum, while η is pseudorapidity (or rapidity). ρ_2 is the two-particle distribution in the intrinsic frame. It can be expressed in terms of the single-particle distributions and the correlation function C

$$\rho_2(\phi_1, \phi_2, x_1, x_2) = \rho(\phi_1, x_1)\rho(\phi_2, x_2)[1 + C(\phi_1, \phi_2, x_1, x_2)]. \quad (9)$$

For simplicity, we neglect higher moments of the azimuthal distribution, v_n , as their contribution to γ will be proportional to $v_n v_m$ which is much smaller than the leading term $\sim v_2$, see Refs. [20, 11]. The resulting single particle density is

$$\rho(\phi, x) = \frac{\rho_0(x)}{2\pi} [1 + 2v_2(x) \cos(2\phi)], \quad (10)$$

where $\rho_0(x)$ and $v_2(x)$ depend solely on $x = (p_t, \eta)$. If $v_2(x) \neq 0$, the single particle distributions depend on the reaction plane. Therefore, the part of the two-particle density (9) involving the two-particle correlation function C depends on the reaction plane even if C is independent of the reaction plane, i.e., $C \sim (\phi_1 - \phi_2)$.

Here we want to concentrate on those correlations that depend only on $\Delta\phi = \phi_1 - \phi_2$, namely the underlying correlation mechanism is insensitive to the reaction plane orientation. The correlation function may be expanded in a Fourier series

$$C(\Delta\phi, x_1, x_2) = \sum_{n=0}^{\infty} a_n(x_1, x_2) \cos(n\Delta\phi), \quad (11)$$

where $a_n(x_1, x_2)$ does not depend on ϕ_1 and ϕ_2 . Substituting (11) and (9) into Eq. (8), we obtain

$$\gamma = \frac{1}{2N^2} \int \rho_0(x_1)\rho_0(x_2)a_1(x_1, x_2)[v_2(x_1) + v_2(x_2)]dx_1dx_2, \quad (12)$$

where $N = \int \rho_0(x)dx$, and we have assumed that $a_n \ll 1$. Similarly, for the reaction plane independent correlation function δ we get

$$\delta = \frac{1}{2N^2} \int \rho_0(x_1)\rho_0(x_2)a_1(x_1, x_2)dx_1dx_2. \quad (13)$$

Equation (12) explains why all correlation mechanisms with a non-zero $a_1(x_1, x_2)$ contribute to γ . For instance, it has been shown that transverse momentum conservation (TMC) leads to a correlation function which depends on $\cos(\Delta\phi)/N_{\text{tot}}$ [21], where N_{tot} is the total number of produced particles. In this case $a_1(x_1, x_2) \propto 1/N_{\text{tot}}$. Let us also emphasize that all correlations that depend on the momentum difference between particles $\Delta\mathbf{k} = |\mathbf{k}_1 - \mathbf{k}_2|$ also contribute to γ . In this case:

$$C(\Delta\mathbf{k}) = C(k_1^2 + k_2^2 - 2k_1k_2 \cos(\Delta\phi)), \quad (14)$$

which naturally leads to a non-vanishing a_1 term.

To summarize, Eq. (12) explains why transverse-momentum conservation [16, 18, 22], local charge conservation [23], resonance- (cluster-) decay [19], and all other

correlations with $\Delta\phi$ dependence contribute to γ . Therefore, any conclusions about possible effects related to the CME require that conventional correlations are under control at least to the level of the observed signal. In addition, it may be helpful if one could separate out the flow dependent contribution to both γ and δ as a next step to isolate a potential CME signal.

3.2 Flow-induced and flow-independent contributions

From the previous discussion it appears rather plausible that the observed charge-dependent correlation patterns in γ and δ contain contributions from more than one source. In particular there are effects whose contributions to these correlations are flow-dependent, for example the transverse momentum conservation (TMC) or the local charge conservation (LCC). On the other hand the CME, if present, is flow independent¹. Let us, therefore, attempt a decomposition of flow-induced and flow-independent contributions as a further step to isolate a possible CME signal.

We first consider correlation effects where the underlying correlation function C is independent of the reaction plane orientation:

$$C(\phi_1, \phi_2) \propto \rho(\phi_1)\rho(\phi_2)C(\phi_1 - \phi_2), \quad (15)$$

where ρ is a single particle distribution. Note that the above is true for both TMC and LCC effects. A correlation effect of this type will contribute to the measured correlators as follows:

$$\gamma_{\alpha,\beta} \sim v_2 F_{\alpha,\beta} \quad , \quad \delta_{\alpha,\beta} \sim F_{\alpha,\beta}, \quad (16)$$

with the factor $F_{\alpha,\beta}$ representing the strength of the effects, and (α, β) is either $++/-$ or $+-$. Both the TMC and the LCC follow this pattern albeit with opposite contributions. Thus F represents the total of all effects of this type.

We should note, however, that the above relation, Eq. (16) is a simplification of the exact relation between γ and $v_2(p_t, \eta)$, which is given in Eq. (12). Since the purpose of the present discussion is to gain some qualitative insight into the various contributions, we assume here that γ is approximately proportional to the integrated v_2 . A quantitative analysis on the other hand would require a careful consideration of the p_t and rapidity dependence of the correlation function $a_1(x_1, x_2)$ and $v_2(x)$, see Eq. (12).

Next we consider possible contributions of the CME type. They would appear in the two-particle density in the following form

$$\rho_2(\phi_1, \phi_2) \propto \sin(\phi_1) \sin(\phi_2), \quad (17)$$

which explicitly involves the reaction plane. This term will contribute to the measured correlators as follows:

$$\gamma_{\alpha,\beta} \sim -H_{\alpha,\beta} \quad , \quad \delta_{\alpha,\beta} \sim H_{\alpha,\beta}, \quad (18)$$

¹ This does not necessarily imply that the CME is the only flow independent contribution.

Fig. 5. The strength factors $F_{\alpha,\beta}$ (left) and $H_{\alpha,\beta}$ (right) extracted from the decomposition analysis (see text for details). The blue boxes and red diamonds are for $++/--$ and $+-$, respectively.

with the factor H representing the strength of the effects. It should be pointed out that besides the CME, there are possibly other effects that may also contribute to the correlators with the above pattern. One example is a possible dipole asymmetry from initial condition fluctuations that preferably aligns with the out-of-plane direction, see Ref. [24] for details. However, this effect will be charge independent, i.e., $H_{++/--} = H_{+-} > 0$, whereas the CME predicts a charge dependence, $H_{++/--} = -H_{+-} > 0$.

Combining the two types of contributions we arrive at the following decomposition for the reaction plane dependent and independent correlation functions,

$$\gamma_{\alpha,\beta} \sim v_2 F_{\alpha,\beta} - H_{\alpha,\beta} \quad , \quad \delta_{\alpha,\beta} \sim F_{\alpha,\beta} + H_{\alpha,\beta}. \quad (19)$$

Given these relations, we may use the STAR data for $\gamma_{\alpha,\beta}$, $\delta_{\alpha,\beta}$, and v_2 to extract the strength factors $F_{\alpha,\beta}$ and $H_{\alpha,\beta}$ as a function of centrality. The result of such a decomposition is shown in Fig. 5.

Following this analysis we make the following observations: (a) Both components are charge dependent, i.e. there is significant difference between $++/--$ and $+-$; (b) In both cases, however, the same-charge and opposite-charge signals are not symmetric with respect to zero. This may indicate that in each category there are likely more than one source of correlations; (c) There is a strong residual centrality dependence for both types component, although the dependence on centrality from v_2 has been

removed. This may indicate that the correlations depend also on the multiplicity, which changes from central to peripheral collisions.

Although, as already noted, the above analysis is qualitative, let us entertain a possible scenario, which would be consistent with the above observations: The flow-induced signals may have two sources, the TMC with $F_{++/--}^{TMC} = F_{+-}^{TMC} < 0$ and the LCC with $F_{++/--}^{LCC} = 0$ and $F_{+-}^{LCC} > |F_{++/--}^{TMC}| > 0$. The flow-independent signals may be from two different sources, the CME with $H_{++/--}^{CME} > 0$ and $H_{+-}^{CME} < 0$ and the dipole asymmetry from fluctuations (DAF) with $H_{++/--}^{DAF} = H_{+-}^{DAF} > 0$. Such a combination would indeed lead to correlations with magnitude and sign in qualitative agreement with the data. However, a quantitative analysis would have to be based on the exact decomposition based on Eq. (12). Alternatively, one may attempt a separation of flow dependent and flow independent contributions in experiment, see [11,20,25].

Recently the STAR collaboration attempted a decomposition along the lines discussed here [8]. They find a difference between the same charge and opposite charge out of plane correlation functions $H_{++/--} - H_{+-}$ which is qualitatively consistent with CME expectations, and which seem to vanish at the lowest beam energy of $\sqrt{s} = 7.7$ GeV. While this is an encouraging observation, the present analysis is based on simplifying assumptions that the flow dependent contribution simply scale with v_2 instead of applying the more complete expression, Eq. (12). In addition, it will be necessary to have measurements below the lowest RHIC energy, in order to establish that the observable stays at zero and does not change sign, which otherwise would be hard to explain in the CME framework. Such measurements can and should be carried out at NICA and FAIR. Finally, it would be interesting to see if a more complete analysis could rule out certain two particle correlation functions, and thus strengthen the evidence for a CME. It would also be vital to develop full-fledged simulations that build on state-of-the-art hydrodynamics with chiral anomaly and quantify both the CME signals and background effects, see e.g., recent efforts in [27,28].

Furthermore, 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 γ this information is not yet available for δ . 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 [15,9]. For example in [15] 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 [26]. In [15] 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 was able to distinguish between an explicit dipole and other correlations.

4 Conclusions

In this contribution we have critically examined the STAR measurement of charge dependent two and three particle correlations and their relevance for local parity violation. We found that for same charge pairs, while the γ correlator measured by STAR has its negative sign and centrality trend similar to that from the Chiral Magnetic Effect, it actually features dominantly an in-plane back-to-back correlations and negligibly small out-of-plane signals across all centralities, which is in contradistinction to the CME-alone predictions. What is most certain as revealed by our analysis, is that the measured correlation patterns appear to be the consequence of multiple effects. Whether the CME is an inevitable component among those could only be established or falsified with substantial future measurements, such as those suggested in the previous section, some of which require very low energies which can only be realized at FAIR and/or NICA. In addition quantitative and realistic simulations of the CME in heavy ion collisions will be necessary.

Acknowledgments

AB was supported by the Ministry of Science and Higher Education (MNiSW), by funding from the Foundation for Polish Science, and by the National Science Centre (Narodowe Centrum Nauki), Grant No. DEC-2014/15/B/ST2/00175, and in part by DEC-2013/09/B/ST2/00497. VK was supported by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, and by the Office of Basic Energy Sciences, Division of Nuclear Sciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and DOE Contract No. DE-AC02-98CH10886. JL was partly supported by the NSF (Grant No. PHY-1352368) and by the RIKEN BNL Research Center.

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