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Remarks on possible local parity violation in heavy ion collisions

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In this Rapid Communication we discuss some observations concerning the possible local parity violation in heavy ion collisions recently announced by the STAR Collaboration. Our results can be summarized as follows (i) the measured correlations for same-charge pairs are mainly in-plane and not out of plane, (ii) if there is a parity-violating component it is large and surprisingly of the same magnitude as the background, and (iii) the observed dependence of the signal on the transverse momentum (p_t) is consistent with a soft boost in p_t and thus in line with expectations from the proposed chiral magnetic effect.

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Introduction. Recently the STAR collaboration announced [1] the results on possible local parity violation in heavy ion collisions. In Refs. [2,3] it was argued that in the hot dense matter created in heavy ion collisions local, instanton, or sphaleron, transitions to QCD vacua with different topological charge may result in metastable domains, where parity is locally violated.

In this Rapid Communication we will solely concentrate on an analysis of the experimental results. We will neither attempt to provide alternative explanations for the observed correlations (such as, e.g., given in Ref. [4]) nor will we discuss the likelihood that the proposed effect may occur in a heavy ion collision. For a detailed discussion of the underlying mechanism and the latest theoretical review of this problem we refer the reader to Ref. [3].

The phenomenon due to local parity violation, which is of relevance for the discussion here, is the so-called chiral magnetic effect [2,3]. It leads to the separation of negatively and positively charged particles along the system's angular momentum (or equivalently the direction of the magnetic field) into two hemispheres separated by the reaction plane. As a result, the system exhibits an electric current along the direction of the angular momentum and thus breaks parity locally in a given event. However, since instanton (sphaleron) and anti-instanton (antisphaleron) transitions occur equally likely, the chiral magnetic current is either aligned or anti-aligned with the angular momentum. As a result, the expectation value of any parity-odd observable, such as $\langle \vec{j}_{\rm CM} \vec{l} \rangle$ vanishes. Here $\vec{j}_{\rm CM}$ is the chiral-magnetic current and $\vec{l}$ is the angular momentum. Consequently, a direct measurement of parity violation even in a small subsystem is impossible. However, one may attempt to identify the existence of these parity violation domains by studying the fluctuations or the variance of a parity-odd observable. Since the variance of a parity-odd observable is parity even, in principle other, genuinely parity-even, effects may contribute and one needs to separate those carefully before being able to draw any conclusions about the existence of local parity-violating domains.

In Ref. [5] Voloshin proposed a method to measure the variance of a parity-odd observable. He suggested measuring the following correlator $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP}) \rangle$, where $\Psi_{\rm RP}$, ϕ_α, and ϕ_β denote the azimuthal angles of the reaction plane and produced charged particles, respectively, see Fig. 1. As we will discuss later, this rather involved correlation function has the advantage that correlations that are independent of the reaction plane do not contribute. As a result, a large fraction of the expected background should cancel. Recently the STAR collaboration reported the measurement of the previous correlation function [1], both integrated over the entire acceptance as well as differential in transverse momentum and pseudorapidity.

This Rapid Communication is organized as follows. First we will analyze the integrated STAR result and will suggest additional measurements necessary to further clarify the situation. We will then concentrate on the p_t differential results and explore to which extent they are consistent with the expected soft phenomena due to the chiral magnetic effect.

The integrated signal. In Ref. [1] the details of the STAR measurement are given. Among other things, STAR shows the results for $\langle \cos(\phi_\alpha - \phi_\beta) \rangle$ and for $\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle$, where $\phi_{\alpha,\beta,c}$ are the azimuthal angles of the produced charged particles. The article gives reasonable arguments that

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP}) \rangle v_{2,c}, \qquad (1)$$

where $\Psi_{\rm RP}$ is the angle of the reaction plane and $v_{2,c}$ characterizes the elliptic anisotropy for the particle with angle ϕ_c.

For the rest of the discussion we will assume that the relation (1) is correct. As a consequence, we will work in a frame where the reaction plane is defined by the $x - z$ coordinates and where the y direction is perpendicular to the reaction plane. In other words, we work in a frame where $\Psi_{\rm RP} = 0$, see Fig. 1. Furthermore, since $\langle \cos(\phi_\alpha - \phi_\beta) \rangle$ is independent of the direction of the reaction plane[1], it will be the same also in the frame where the reaction plane is specified

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[1]Indeed $\langle \cos(\phi_\alpha - \phi_\beta) \rangle \equiv \langle \cos([\phi_\alpha - \Psi_{\rm RP}] - [\phi_\beta - \Psi_{\rm RP}]) \rangle$.

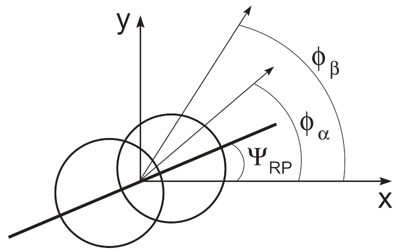

FIG. 1. The transverse plain in a collision of two heavy ions. $\Psi_{\rm RP}$, ϕ_α, and ϕ_β denote the azimuthal angles of the reaction plane and produced charged particles, respectively.

(e.g., $\Psi_{\rm RP} = 0$). Thus within our frame we have to consider the following two-particle correlations

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

STAR measured both these correlation functions for same sign, $(+,+),(-,-)$, and opposite sign, $(+,-)$, pairs of charged particles. Qualitatively the data for Au + Au collisions can be characterized as follows.

(i) For same-sign pairs:

$$\langle\cos(\phi_\alpha + \phi_\beta)\rangle_{\rm same} \simeq \langle\cos(\phi_\alpha - \phi_\beta)\rangle_{\rm same} < 0. \tag{3}$$

Using Eq. (2) this implies

$$\begin{aligned}\langle\sin(\phi_\alpha)\sin(\phi_\beta)\rangle_{\rm same} &\simeq 0,\\ \langle\cos(\phi_\alpha)\cos(\phi_\beta)\rangle_{\rm same} &< 0.\end{aligned} \tag{4}$$

(ii) For opposite-sign pairs we find that

$$\begin{aligned}\langle\cos(\phi_\alpha + \phi_\beta)\rangle_{\rm opposite} &\simeq 0,\\ \langle\cos(\phi_\alpha - \phi_\beta)\rangle_{\rm opposite} &> 0.\end{aligned} \tag{5}$$

Again, using Eq. (2), this means

$$\langle\sin(\phi_\alpha)\sin(\phi_\beta)\rangle_{\rm opposite} \simeq \langle\cos(\phi_\alpha)\cos(\phi_\beta)\rangle_{\rm opposite} > 0. \tag{6}$$

The actual data decomposed into the above components are shown in Fig. 2.

The fact that for the same-charge pairs the sinus term in Eq. (4) (see Fig. 2) is essentially zero whereas the cosine term is finite, tells us that the observed correlations are actually *in plane* rather than out of plane. This is contrary to the expectation from the chiral magnetic effect, which results in same-charge correlation out of plane. In addition, since the cosine term is negative, the in-plane correlations are stronger for back-to-back pairs than for small angle pairs. Second, we see that for opposite-charge pairs the in-plane and out-of-plane correlations are virtually identical. This is difficult to comprehend given that there is a sizable elliptic flow in these collisions. At present, there is no simple explanation for either of these observations. However, they may be explained by a cluster model, which requires several, not unreasonable, assumptions [4].

One may ask if there is room for a parity-violating component if for the same sign $\langle\sin(\phi_\alpha)\sin(\phi_\beta)\rangle_{\rm same} \simeq 0$ (i.e., the signal is in-plane rather than out of plane). Following the argument of Refs. [1,5], we can always write

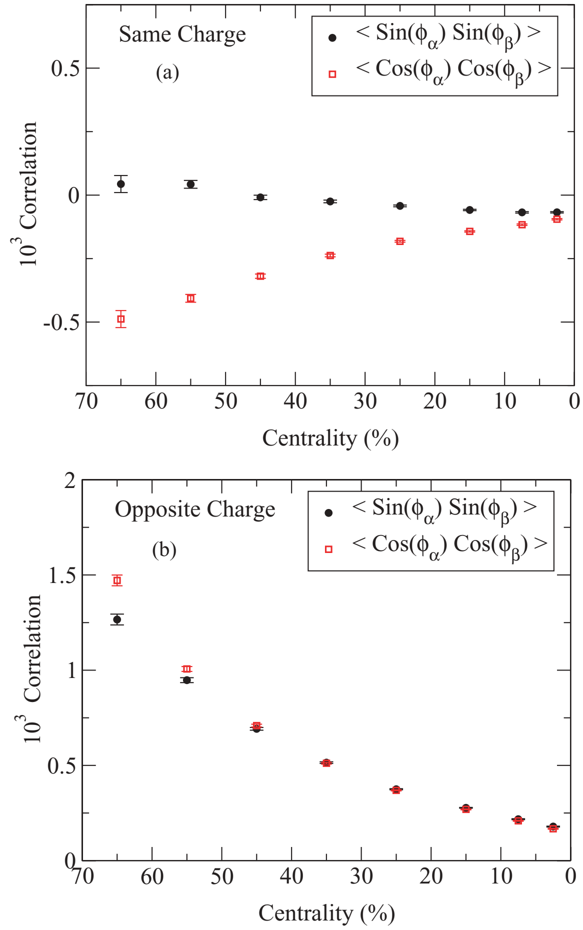

FIG. 2. (Color online) Correlations in-plane $\langle\cos(\phi_\alpha)\cos(\phi_\beta)\rangle$ and out of plane $\langle\sin(\phi_\alpha)\sin(\phi_\beta)\rangle$ for (a) same and (b) opposite-charge pairs in Au + Au collisions. As can be seen the correlations for same-charge pairs are mainly in-plane.

$$\langle\sin(\phi_\alpha)\sin(\phi_\beta)\rangle_{\rm same} = B_{\rm out} + P, \tag{7}$$

where P is the part of the correlation that is caused by the parity violation (at this stage we do not claim that $P \neq 0$) and $B_{\rm out}$ represents all other contributions by correlations projected on the direction perpendicular to the reaction plane. Denoting the correlations in-plane $\langle\cos(\phi_\alpha)\cos(\phi_\beta)\rangle_{\rm same}$ by $B_{\rm in}$ we obtain

$$\begin{aligned}\langle\cos(\phi_\alpha + \phi_\beta)\rangle_{\rm same} &= [B_{\rm in} - B_{\rm out}] - P,\\ \langle\cos(\phi_\alpha - \phi_\beta)\rangle_{\rm same} &= [B_{\rm in} + B_{\rm out}] + P.\end{aligned} \tag{8}$$

The advantage of $\langle\cos(\phi_\alpha + \phi_\beta)\rangle$ is obvious. The background is $B_{\rm in} - B_{\rm out}$, meaning that all correlations that do not depend on the reaction plane orientation cancel. The STAR collaboration studied many known sources of reaction-plane-dependent correlations and all effects produce $B_{\rm in} - B_{\rm out}$, which is much smaller than the observed signal. We note, however, that at present the background is not understood since none of the present models are able to explain the value of $\langle\cos(\phi_\alpha - \phi_\beta)\rangle$.

Following the previous argument, however, immediately implies that [using Eqs. (4) and (7)]

$$P \simeq -B_{\mathrm{out}} \simeq -B_{\mathrm{in}}, \tag{9}$$

that is, the parity-violating effect has to be precisely of the same magnitude as all other standard correlations. This relation is quite an unexpected coincidence. It means that the parity signal is quite strong and consequently should also be visible in $\langle \cos(\phi_\alpha - \phi_\beta)\rangle_{\mathrm{same}}$ if the background is well understood.

In our view, it is mandatory to explore if the relation, Eq. (9), is just a coincidence or an indication of potential problems with the present interpretation of the data. To answer this question it is essential to analyze the correlation function $\langle \cos(\phi_\alpha - \phi_\beta)\rangle_{\mathrm{same}}$ differentially in transverse momentum and pseudorapidity as it was already done for $\langle \cos(\phi_\alpha + \phi_\beta)\rangle_{\mathrm{same}}$. Should relation (9) persist also for the differential correlations, one will have to conclude that the proposed parity-violating effect is not seen in the data.

Transverse momentum dependence. The STAR collaboration also presented [1] the measurement of $\langle \cos(\phi_\alpha + \phi_\beta)\rangle$ in midcentral Au + Au collisions as a function of $p_+ = (p_{t,\alpha} + p_{t,\beta})/2$ and $p_- = |p_{t,\alpha} - p_{t,\beta}|$, where $p_{t,\alpha}$ and $p_{t,\beta}$ are the absolute values of the particles momenta. Qualitatively the data can be characterized as follows.[2]

(i) For same-sign pairs in the range $0 < p_+, p_- < 2.2$ GeV

$$\begin{aligned} \langle \cos(\phi_\alpha + \phi_\beta)\rangle_{p_+,\ \mathrm{same}} &\propto p_+ \\ \langle \cos(\phi_\alpha + \phi_\beta)\rangle_{p_-,\ \mathrm{same}} &\simeq \mathrm{const.} \end{aligned} \tag{10}$$

(ii) For opposite-sign pairs the signal versus p_+ and p_- is consistent with zero.

One will expect [1,2] that the parity-violating signal should be a soft, low p_t phenomenon. Thus the observed increase of the signal for same-sign pairs with p_+ seems to be inconsistent with the chiral magnetic effect. As we will show, such a conclusion is not necessarily correct and the true signal may indeed be consistent with the expected low p_t dynamics.

Indeed, by definition

$$\langle \cos(\phi_\alpha + \phi_\beta)\rangle = \frac{N_{\mathrm{corr}}}{N_{\mathrm{all}}}, \tag{11}$$

where N_{corr} is the number of correlated pairs [via $\cos(\phi_\alpha + \phi_\beta)$] and N_{all} is the number of all pairs. The latter can be easily approximated by [$p_+ = (p_{t,\alpha} + p_{t,\beta})/2$ and $p_- = |p_{t,\alpha} - p_{t,\beta}|$]

$$\begin{aligned} N_{\mathrm{all}}(p_+) \propto &\int d^2 p_{t,\alpha} d^2 p_{t,\beta} \exp\left(-\frac{p_{t,\alpha}}{T}\right) \exp\left(-\frac{p_{t,\beta}}{T}\right) \\ &\times \delta(2p_+ - [p_{t,\alpha} + p_{t,\beta}]) \propto p_+^3 e^{-2p_+/T}, \end{aligned} \tag{12}$$

and

$$\begin{aligned} N_{\mathrm{all}}(p_-) \propto &\int d^2 p_{t,\alpha} d^2 p_{t,\beta} \exp\left(-\frac{p_{t,\alpha}}{T}\right) \exp\left(-\frac{p_{t,\beta}}{T}\right) \\ &\times \delta(p_- - |p_{t,\alpha} - p_{t,\beta}|) \propto T^2 e^{-(p_-/T)}(p_- + T), \end{aligned} \tag{13}$$

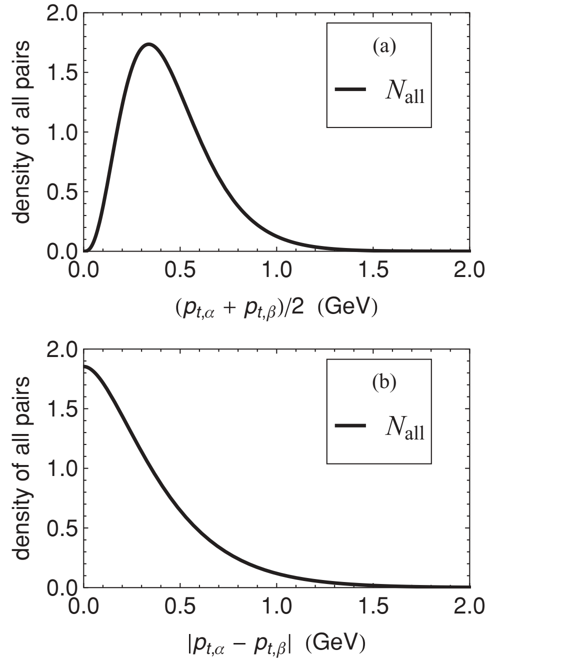

FIG. 3. The distributions of all charge pairs versus $(p_{t,\alpha} + p_{t,\beta})/2$ and $|p_{t,\alpha} - p_{t,\beta}|$, respectively.

where in the following calculations we take $T = 0.22$ GeV.[3]

The calculated distributions of all pairs versus $(p_{t,\alpha} + p_{t,\beta})/2$ and $|p_{t,\alpha} - p_{t,\beta}|$ are presented in Fig. 3. It is worth noticing that both functions are concentrated in the small p_t region, reflecting typical thermal distributions for p_- and p_+. Due to the soft nature of the chiral magnetic effect, one expects that the distributions in p_- and p_+ for the correlated particles should not differ much from the underlying thermal distributions. This is indeed the case as we will demonstrate next.

To estimate the distribution of correlated same-sign pairs it is sufficient to multiply Eq. (10) by the expressions (12) and (13), respectively. Consequently we obtain

$$\begin{aligned} N_{\mathrm{corr}}(p_-) &\propto N_{\mathrm{all}}(p_-), \\ N_{\mathrm{corr}}(p_+) &\propto p_+ N_{\mathrm{all}}(p_+). \end{aligned} \tag{14}$$

As can be seen, the dependence of the number of correlated same pairs versus $|p_{t,\alpha} - p_{t,\beta}|$ is identical to the dependence of all pairs presented in Fig. 3. Clearly the signal is concentrated in the low p_t region and indeed is unchanged from a thermal distribution. In Fig. 4 the dependence of the number of same-sign pairs versus $(p_{t,\alpha} + p_{t,\beta})/2$ is compared with the dependence of all pairs (previously shown in Fig. 3). We find that the momenta of correlated particles are slightly shifted to the higher p_t and the shape is roughly similar. The momentum shift required by the data is $\delta p_+ \simeq 150$ MeV, which can conceivably be due to the large magnetic field, although it is somewhat on the high end of what one will naively expect from electromagnetic phenomena.

[2] Here we are only interested in the p_t dependence of the signal, not in the overall normalization.

[3] It corresponds to the average transverse momentum of the pions $\langle p_t \rangle = 0.45$ GeV.

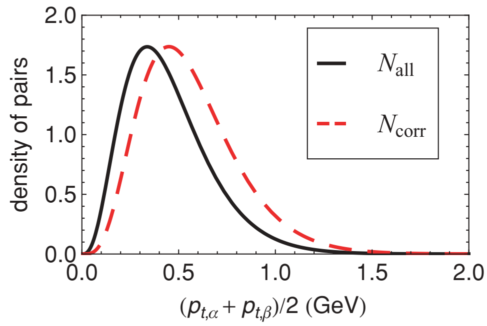

FIG. 4. (Color online) Distribution of all pairs (solid line) compared with the distribution of same-sign correlated pairs (dashed line). Both functions are concentrated in the low p_t region.

Conclusion. In this Rapid Communication we discuss several aspects of the recent measurement of possible local parity violation in Au + Au collisions by the STAR Collaboration. We made the following three observations:

(i) For particles with the same charge STAR sees large negative correlations in-plane $\langle\cos(\phi_\alpha)\cos(\phi_\beta)\rangle_{\rm same}$ and very small correlations out of plane $\langle\sin(\phi_\alpha)\sin(\phi_\beta)\rangle_{\rm same}$. For opposite-sign correlations in-plane and out-plane are both positive and of the same magnitude.

(ii) If there is indeed a parity-violating component in the STAR data it has to be of the same magnitude as all other "trivial" correlations projected on the direction perpendicular to the reaction plane. This may be a pure coincidence or an indication that the present interpretation of the data as a signal for local parity violation needs to be revised. To investigate this problem in more detail we need differential distribution (versus pseudorapidity or transverse momenta) of $\langle\cos(\phi_\alpha+\phi_\beta)\rangle$ and $\langle\cos(\phi_\alpha-\phi_\beta)\rangle$ at the same time.

(iii) We also argue that the distribution of the number of correlated pairs is concentrated in the low p_t region (i.e., $p_t < 1$ GeV). It is not inconsistent with the predictions of the chiral magnetic effect.

At present, the data from the STAR Collaboration does not allow for a definitive conclusion about the presence of local parity violation. The measurement of the correlation function $\langle\cos(\phi_\alpha-\phi_\beta)\rangle$ differential in transverse momentum and pseudorapidity is absolutely essential to further distinguish between trivial correlations and those due to the chiral magnetic effect.

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[1] B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. Lett. **103**, 251601 (2009); arXiv:0909.1717 [nucl-ex].
[2] K. Fukushima, D. E. Kharzeev, and H. J. Warringa, Phys. Rev. D **78**, 074033 (2008); D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nucl. Phys. **A803**, 227 (2008).
[3] D. E. Kharzeev, Annals Phys. **325**, 205 (2010).
[4] F. Wang, arXiv:0911.1482 [nucl-ex].
[5] S. A. Voloshin, Phys. Rev. C **70**, 057901 (2004).