Suppression of elliptic-flow-induced correlations in an observable of possible local parity violation

Adam Bzdak

Phys. Rev. C **85**, 044919 — Published 19 April 2012

DOI: 10.1103/PhysRevC.85.044919

Suppression of elliptic flow induced correlations in an observable of possible local parity violation

Adam Bzdak
RIKEN BNL Research Center
Brookhaven National Laboratory*

Abstract

We show that fluctuations in elliptic anisotropy in peripheral heavy-ion collisions can be used to significantly reduce the contribution of transverse-momentum conservation, and of all background effects independent on the orientation of the reaction plane, from an observable of the chiral magnetic effect. We argue that for a given impact parameter, the magnetic field is approximately independent of the fluctuating shape of the fireball.

1. The main feature of the chiral magnetic effect (CME) [1] is the existence of an electric current parallel (or anti-parallel) to the direction of magnetic field produced in heavy-ion collisions [2], see also [1], [3]. Consequently, charge separation can be observed in the direction perpendicular to the reaction plane. Recently, evidence for the CME was found in lattice QCD calculations [4]. A detailed discussion of this effect was given in Ref. [5].

As discussed in Ref. [6], such charge separation can be observed via the following two-particle correlator

$$\gamma = \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle \,, \tag{1}$$

*Address: Upton, NY 11973, USA; email: abzdak@bnl.gov

where Ψ_{RP}, ϕ_1, and ϕ_2, respectively, denote the azimuthal angles of the reaction plane, and the two charged particles produced. Alternative observables were proposed in Refs. [7, 8] (see last section). Recently, the STAR collaboration measured γ and their result [9, 10] is qualitatively consistent with the CME expectation; however, the interpretation of these data still are debatable, see e.g., [11, 12, 13, 14, 15, 16, 17, 18]. The interpretation of experimental results is not simple because practically all two-particle correlations contribute to γ, as seen from (here $\Psi_{RP} = 0$)

$$\gamma = \langle \cos(\phi_1)\cos(\phi_2) \rangle - \langle \sin(\phi_1)\sin(\phi_2) \rangle . \tag{2}$$

Indeed, in the presence of elliptic anisotropy [19], both terms can differ even though the correlation mechanism itself is not directly sensitive to the orientation of the reaction plane.

In this paper, we discuss this problem in detail. In the next Section, we undertake explicit calculations to quantify the contribution of elliptic anisotropy to γ. Next, we argue that in peripheral heavy-ion collisions (where the CME is considered to have a maximum strength [1]) we expect large fluctuations in elliptic flow (v_2) such that it allows us to deduct the v_2-driven background from γ. We also show that the changing shape of the fireball, at a given impact parameter, does not change the contribution of the CME to γ. Finally, we present a Monte Carlo model, wherein we evaluate the contribution of transverse-momentum conservation to γ at vanishing elliptic anisotropy ($v_2 \to 0$). In the last section we give our comments and conclusions.

2. By definition

$$\gamma = \frac{\int \rho_2(\phi_1, \phi_2, x_1, x_2, \Psi_{RP}) \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) d\phi_1 d\phi_2 dx_1 dx_2}{\int \rho_2(\phi_1, \phi_2, x_1, x_2, \Psi_{RP}) d\phi_1 d\phi_2 dx_1 dx_2}, \tag{3}$$

where ρ_2 is the two-particle distribution at a given angle of the reaction plane, Ψ_{RP}. To make our notation shorter, we denote $x = (p_t, \eta)$ and $dx = p_t dp_t d\eta$, where p_t is the absolute value of transverse-momentum, while η is pseudorapidity. The distribution ρ_2 can be expressed via the correlation function C

$$\rho_2(\phi_1, \phi_2, x_1, x_2, \Psi_{RP}) = \rho(\phi_1, x_1, \Psi_{RP}) \rho(\phi_2, x_2, \Psi_{RP}) [1 + C(\phi_1, \phi_2, x_1, x_2)], \tag{4}$$

with the single-particle distribution[1]

$$\rho(\phi, x, \Psi_{RP}) = \frac{\rho_0(x)}{2\pi}[1 + 2v_2(x)\cos(2\phi - 2\Psi_{RP})], \tag{5}$$

where $\rho_0(x)$ does not depend on ϕ and Ψ_{RP}. We study only those correlations that do not depend on the reaction plane, i.e., C only depends on $\Delta\phi = \phi_1 - \phi_2$. Next we expand C in a Fourier series

$$C(\Delta\phi, x_1, x_2) = \sum\nolimits_{n=0}^{\infty} a_n(x_1, x_2)\cos(n\Delta\phi), \tag{6}$$

where $a_n(x_1, x_2)$ does not depend on ϕ_1 and ϕ_2. Substituting (6) and (4) into Eq. (3), we obtain

$$\gamma = \frac{1}{2N^2}\int \rho_0(x_1)\rho_0(x_2)a_1(x_1, x_2)[v_2(x_1) + v_2(x_2)]dx_1 dx_2, \tag{7}$$

where $N = \int \rho_0(x)dx$ and we assume that $1 + a_n \approx 1$. As seen from Eq. (7), all correlations with non-zero $a_1(x_1, x_2)$ contribute to γ, even if the underlying correlation mechanisms do not depend on the orientation of the reaction plane. This finding explains why transverse-momentum conservation [11, 14, 18], local charge-conservation [12], resonance- (cluster-) decay [15], and all other correlations with $\Delta\phi$ dependence contribute to γ. However, as pointed out recently in Ref. [20], those correlations can be removed from γ by taking only those events where $v_2(x) \approx 0$. We note that $v_2(x)$ is defined solely through Eq. (5), and it can be positive or negative.

Taking the CME into account[2]

$$\rho_\chi(\phi, x, \Psi_{RP}) = \frac{\rho_0(x)}{2\pi}\left[1 + 2v_2(x)\cos(2\phi - 2\Psi_{RP}) + 2\chi d(x)\sin(\phi - \Psi_{RP})\right], \tag{8}$$

we obtain,

$$\begin{aligned}\gamma &= -\frac{1}{N^2}\left[\int d(x)\rho_0(x)dx\right]^2 + \\ & \frac{1}{2N^2}\int \rho_0(x_1)\rho_0(x_2)a_1(x_1, x_2)[v_2(x_1) + v_2(x_2)]dx_1 dx_2,\end{aligned} \tag{9}$$

[1] Higher v_n results in terms proportional to $v_2 v_4$, $v_4 v_6$ etc., and can be neglected, see Eq. (7).

[2] The value of χ flips between -1 and $+1$ so that $\frac{1}{2}\sum_\chi \rho_\chi = \rho$, defined in Eq. (5).

wherein the first term represents the CME, and the second term is the elliptic-anisotropy-driven background.

3. We expected that elliptic anisotropy would be correlated with the participant eccentricity ϵ_2 [21]. In the center of mass of the wounded nucleons, ϵ_2 is given by

$$\epsilon_2 = \frac{\sqrt{\left(\sum_i r_i^2 \cos(2\phi_i)\right)^2 + \left(\sum_i r_i^2 \sin(2\phi_i)\right)^2}}{\sum_i r_i^2}, \tag{10}$$

wherein the wounded nucleons are characterized by their radii, r_i, and their azimuthal angles, ϕ_i.

In Fig. 1, we present the calculated[3] ϵ_2 distribution in Au+Au collisions at $\sqrt{s}$ = 200 GeV with b = 10 fm (impact parameter). Accordingly, even at b = 10 fm, we obtain a broad range of ϵ_2 (and v_2)[4] that can be used to significantly change the background present in the second term of Eq. (9).

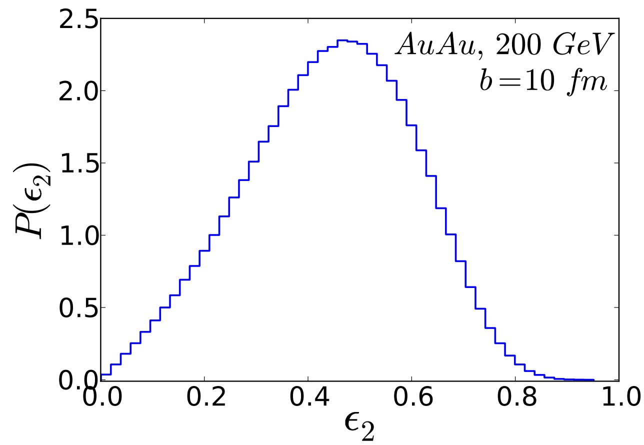

Figure 1: Normalized density distribution of the participant eccentricity ϵ_2 at the impact parameter b = 10 fm in Au+Au collisions at $\sqrt{s}$ = 200 GeV.

However, we wanted to remove this background under the condition that the contribution from the CME is approximately unchanged. To verify this,

[3]We use the Monte Carlo Glauber calculation with standard parameters [22].

[4]In 3D event-by-event hydrodynamics [23], $\langle v_2 \rangle = 0.08$ and $[\langle v_2^2 \rangle - \langle v_2 \rangle^2]^{1/2} = 0.04$ for $40 - 50\%$ centrality ($b \approx 10$ fm) in Au+Au collisions.

we calculated[5] the out-of-plane component of the magnetic field B_y at $t = 0$ (time) as a function of ϵ_2. As seen in Fig. 2, the magnetic field from wounded- and spectator- protons[6] are approximately constant (in comparison to v_2 that scales linearly with ϵ_2) in the broad range of ϵ_2. We conclude that fluctuating v_2 in peripheral collisions will allow us to study the v_2 dependence of γ at an approximately constant strength of the CME.

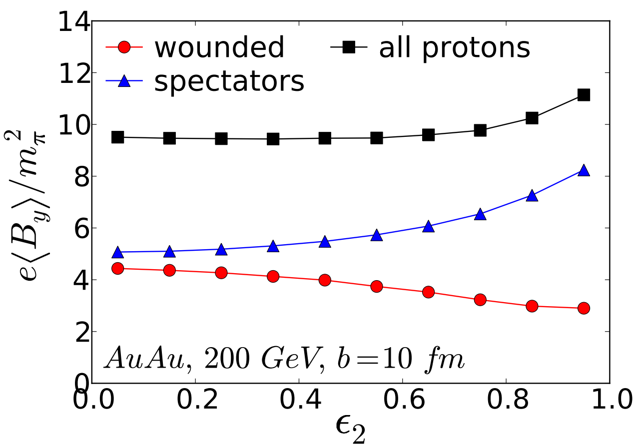

Figure 2: The out-of-plane component of magnetic field at $b = 10$ fm in Au+Au collisions at $\sqrt{s} = 200$ GeV as a function of the participant eccentricity ϵ_2. Contributions from the wounded- and spectator- protons are depicted separately.

In Figs. 1, 2 we made our calculations at a given impact parameter. In an actual experiment, we can select our peripheral collisions, e.g., by the number of particles produced at midrapidity. We consider that our conclusions also will hold in this situation.

4. As an example, we calculated γ as a function of v_2 in a model with only transverse-momentum conservation and elliptic anisotropy.[7] As shown in

[5]The details of our calculation are presented in Ref. [24].

[6]Both sources that are expected to contribute differently during the evolution of the fireball [1]

[7]The calculations presented in this section are for illustrative purposes only, and should not be compared with the STAR data.

[11, 14, 18], this effect contributes significantly to γ and reasonably describes the p_t and η dependence.

We sampled $N_{all} = 50$ particles with p_t according to the thermal distribution $p_t e^{-p_t/T}$ with $2T = 0.45$ MeV, and ϕ according to $1 + 2v_2(p_t)\cos(2\phi)$. We took $v_2(p_t) = 0.14p_t$ for $p_t < 2$ GeV and $v_2(p_t) = 0.28$ for $p_t > 2$ GeV, so that we obtained the integrated $v_2 \approx 0.06$. Next, we imposed transverse-momentum conservation[8] and calculated γ as a function of selected $v_2 = \frac{1}{N_{obs}} \sum_{i=1}^{N_{obs}} \cos(2\phi_i)$, where N_{obs} is the number of observed particles (selected randomly from N_{all}). Owing to the statistical fluctuations, we obtained a broad range of v_2 that allows us to test Eq. (7).

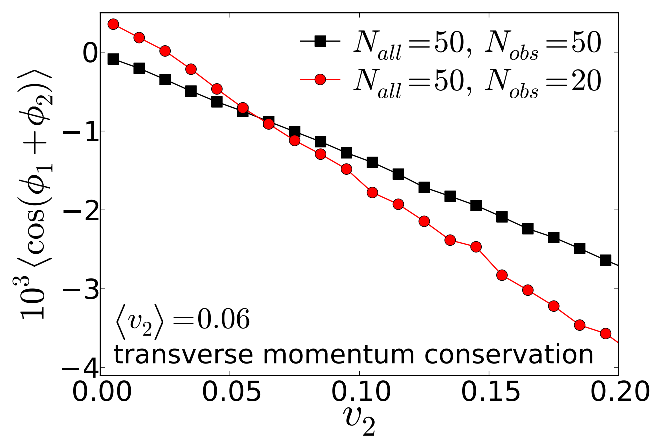

Figure 3: The contribution of transverse-momentum conservation to γ as a function of v_2. The momentum is conserved for N_{all} particles and γ is calculated for N_{obs} (observed) particles, selected randomly from N_{all}.

As seen from Fig. 3, $\gamma \to 0$ as $v_2 \to 0$ for $N_{all} = N_{obs} = 50$. However, it might be surprising that for $N_{obs} = 20$, γ becomes slightly positive as $v_2 \to 0$. In Ref. [14] the contribution of conserving transverse-momentum was calculated analytically, and was shown to scale not only with v_2 in the region where particles are observed, but also with v_2 in the whole phase-space

$$\gamma \sim -\frac{1}{N_{all}} \left[2\bar{v}_{2,\Omega} - \bar{\bar{v}}_{2,F}\right] , \tag{11}$$

[8]We accepted only those events where the total (summed over N_{all} particles) $|p_{t,x}| < 0.5$ GeV and $|p_{t,y}| < 0.5$ GeV.

where $\bar{v}_2 \sim \int \rho_0(x) v_2(x) p_t dx$, $\bar{\bar{v}}_2 \sim \int \rho_0(x) v_2(x) p_t^2 dx$ and $x = (p_t, \eta)$, $dx = p_t dp_t d\eta$. The indexes F and Ω indicate that integrations are performed over full phase-space (F) or the phase space wherein particles are measured (Ω), respectively. When we calculate γ for all produced particles, $\Omega = F$, then $v_{2,\Omega} = 0$ implies $v_{2,\Omega}(p_t, \eta) = 0$ and $\bar{v}_{2,\Omega} = \bar{\bar{v}}_{2,F} = 0$. Consequently, $\gamma = 0$ at $v_{2,\Omega} = 0$. However, if we measure only a fraction of all particles, then for $v_{2,\Omega} = 0$ (and $\bar{v}_{2,\Omega} = 0$), $\bar{\bar{v}}_{2,F}$ can differ from zero (positive) and $\gamma \sim \bar{\bar{v}}_{2,F}/N_{all} > 0$, as seen from Eq. (11).

5. Several comments are warranted:

(i) Very recently, an observable related to γ was studied as a function of elliptic anisotropy [20]. This finding argued that for mid-peripheral Au+Au collisions $\gamma < 0$ at $v_2 = 0$ for same-charge pairs, which is consistent with the CME.

(ii) Even if $\gamma < 0$ at $v_2 = 0$ for same-charge pairs, it does not imply the existence of the CME. It only indicates the presence of some correlation mechanism that explicitly depends on the orientation of the reaction plane. To *measure* the CME, a different observable is needed, e.g., the multiparticle charge-sensitive correlator [7] or direct measurements of the electric dipole [8].

(iii) As argued in Ref. [25], central U+U collisions also can be used to distinguish between effects driven by elliptic anisotropy and the CME. In the present paper, we considered only peripheral collisions, where the CME and fluctuations in v_2 are expected to be the most visible. Both methods can be used independently to reduce the contribution of elliptic anisotropy.

(iv) In this paper, we proposed a way to remove the elliptic-flow-induced background from the correlator γ. However, we note that in Ref. [7] a new multiparticle charge-sensitive correlator C_c was proposed that is insensitive to correlations due to (elliptic) flow, jets, or momentum conservation. The measurement of C_c together with γ (with removed background) could provide an important information about a possible signal of local parity violation.

In summary, we demonstrated that fluctuations in elliptic anisotropy in (mid-) peripheral heavy-ion collisions can be used effectively to reduce the contribution of v_2-induced correlations from the two-particle correlator (1). We showed that at a given impact parameter, the magnetic field produced in heavy-ion collisions depends weakly on the participant eccentricity, in contrast to the value of v_2. We also discussed the contribution of transverse-momentum conservation to γ at a vanishing v_2. Preliminary experimental analysis [20] suggests the presence of a correlation mechanism that does not scale with elliptic anisotropy.

Acknowledgments

We are grateful to Vladimir Skokov for numerous discussions. Correspondence with Scott Pratt and Sergei Voloshin is highly appreciated. We thank Ron Longacre for discussions about his recent paper. This investigation was supported by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886 and by the grant N N202 125437 of the Polish Ministry of Science and Higher Education (2009-2012).

References

[1] D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A **803**, 227 (2008)

[2] J. Rafelski and B. Muller, Phys. Rev. Lett. **36**, 517 (1976).

[3] V. Skokov, A. Illarionov and V. Toneev, Int. J. Mod. Phys. A **24**, 5925 (2009)

[4] P. V. Buividovich, M. N. Chernodub, E. V. Luschevskaya and M. I. Polikarpov, Phys. Rev. D **81**, 036007 (2010)

[5] D. E. Kharzeev, Annals Phys. **325**, 205 (2010)

[6] S. A. Voloshin, Phys. Rev. C **70**, 057901 (2004)

[7] N. N. Ajitanand, R. A. Lacey, A. Taranenko and J. M. Alexander, Phys. Rev. C **83**, 011901 (2011)

[8] J. Liao, V. Koch and A. Bzdak, Phys. Rev. C **82**, 054902 (2010)

[9] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **103**, 251601 (2009)

[10] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **81**, 054908 (2010)

[11] S. Pratt, S. Schlichting and S. Gavin, Phys. Rev. C **84**, 024909 (2011)

[12] S. Schlichting and S. Pratt, Phys. Rev. C **83**, 014913 (2011)

[13] A. Bzdak, V. Koch and J. Liao, Phys. Rev. C **81**, 031901 (2010)

[14] A. Bzdak, V. Koch and J. Liao, Phys. Rev. C **83**, 014905 (2011)

[15] F. Wang, Phys. Rev. C **81**, 064902 (2010)

[16] B. Muller and A. Schafer, Phys. Rev. C **82**, 057902 (2010)

[17] D. Teaney and L. Yan, Phys. Rev. C **83**, 064904 (2011)

[18] G. -L. Ma and B. Zhang, Phys. Lett. B **700**, 39 (2011)

[19] S. A. Voloshin, A. M. Poskanzer and R. Snellings, arXiv:0809.2949 [nucl-ex].

[20] R. Longacre, arXiv:1112.2139 [nucl-th].

[21] B. Alver *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **98**, 242302 (2007)

[22] B. Alver, M. Baker, C. Loizides and P. Steinberg, arXiv:0805.4411 [nucl-ex].

[23] Private communication with Bjoern Schenke.

[24] A. Bzdak and V. Skokov, arXiv:1111.1949 [hep-ph].

[25] S. A. Voloshin, Phys. Rev. Lett. **105**, 172301 (2010)