Implications of p+Pb measurements on the chiral magnetic effect in heavy ion collisions

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To CME or not to CME? Implications of p+Pb measurements on the chiral magnetic effect in heavy ion collisions

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The Chiral Magnetic Effect (CME) is a fundamental prediction of QCD, and various observables have been proposed in heavy ion collisions to access this physics. Recently the CMS Collaboration [1] has reported results from p+Pb collisions at 5.02 TeV on one such observable, the three-point correlator. The results are strikingly similar to those measured at the same particle multiplicity in Pb+Pb collisions, which have been attributed to the CME. This similarity, combined with two key assumptions about the magnetic field in p+Pb collisions, presents a major challenge to the CME picture. These two assumptions as stated in the CMS paper are (1) that the magnetic field in p+Pb collisions is smaller than that in Pb+Pb collisions and (2) that the magnetic field direction is uncorrelated with the flow angle. We test these two postulates in the Monte Carlo Glauber framework and find that the magnetic fields are not significantly smaller in central p+Pb collisions, however the magnetic field direction and the flow angle are indeed uncorrelated. The second finding alone gives strong evidence that the three-point correlator signal in Pb+Pb and p+Pb is not an indication of the CME. Similar measurements in d+Au over a range of energies accessible at RHIC would be elucidating. In the same calculational framework, we find that even in Pb+Pb collisions, where the magnetic field direction and the flow angle are correlated, there exist large inhomogeneities that are on the size scale of topological domains. These inhomogeneities need to be incorporated in any detailed CME calculation.

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I. INTRODUCTION

The search for locally parity (P) violating effects in heavy ion collisions, such as the Chiral Magnetic Effect (CME), is a major thrust of research in the field of heavy ion physics; for recent reviews see for example Refs. [2, 3]. The QCD vacuum is highly non-trivial, comprising a spectrum of topologically distinct states characterized by the Chern-Simons number N_{CS}. When the gluon field transitions from one topological state to another, a chiral imbalance is created, described by the relation $\Delta N_{CS} = Q_w = N_L - N_R$, where Q_w is the topological charge and N_L and N_R are the number of left and right handed quarks, respectively. The CME is an electric current either parallel or antiparallel to the magnetic field, summarized by the relation

$$\vec{J_V} = \frac{N_c}{2\pi}\mu_A \vec{B}, \tag{1}$$

where J_V is the electric current, N_c is the number of colors (3 in the case of QCD), μ_A is the axial chemical potential (which encodes the strength of the chiral imbalance), and B is the magnetic field induced by the protons in the target and projectile nuclei.

In semi-central A+A collisions, the magnetic field is exactly perpendicular to the impact parameter vector in the case of smooth geometry. Fluctuations in the nucleon positions are expected to cause small fluctuations in this relation. The conventional Fourier series [4] used to describe the azimuthal distribution of particles explicitly omits the P-odd sine terms, but it is straightforward [5] to add them. In this case one has

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty}[v_n \cos(n(\phi-\psi)) + a_n \sin(n(\phi-\psi))], \tag{2}$$

where ψ is some symmetry plane (different symmetry planes can be chosen to address different physical mechanisms), and $v_n = \langle\cos(n(\phi-\psi))\rangle$ are the familiar harmonic coefficients and $a_n = \langle\sin(n(\phi-\psi))\rangle$ are the P-odd terms. In the case of the CME, the first term a_1 is the term of interest. For a given topological charge, the positive and negative particles travel in opposite directions and therefore a_1^+ and a_1^- should have opposite sign. However, the sign of either of them depends on the sign of the topological charge, which fluctuates event-by-event about an average of $\langle Q_w\rangle = 0$. To that end, Voloshin proposed [5] to study 2-particle correlations, where one always expects $\langle a_1^\pm a_1^\pm\rangle > 0$ and $\langle a_1^\pm a_1^\mp\rangle < 0$. To measure these quantities, one can measure the three-point correlator

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\psi_{RP})\rangle = \langle v_1^\alpha v_1^\beta\rangle - \langle a_1^\alpha a_1^\beta\rangle, \tag{3}$$

where ϕ_α is the azimuthal angle of one particle, ϕ_β is the azimuthal angle of a second particle, and ψ_{RP} is the reaction plane angle, which is defined as pointing along the direction of the impact parameter vector. The correlator is a three-point correlator in that the first two points are the two particles of interest and the third point is the symmetry plane. In cases where one uses a single particle to determine the symmetry plane, one has the more specific case of a three-particle correlator. Note that for

clarity we omit non-flow and assume the magnetic field direction is perfectly correlated with the reaction plane angle ψ_{RP} in this equation. In experiment, one can neither measure the magnetic field direction nor the reaction plane angle directly. Instead we measure the second harmonic flow plane, and use that in the three-point correlator as

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_2) \rangle, \tag{4}$$

where ψ_2 is the second harmonic event plane. In nuclear collisions, ψ_2 is strongly correlated with ψ_{RP}, but they are not equal due to event by event fluctuations in the nucleon positions [6]. Assuming the measured ψ_2 is correlated with the magnetic field direction, as expected in Pb+Pb collisions, one will get a net contribution to the correlator. In contrast, background correlations that are independent of the magnetic field and ψ_2 should cancel out because the CME correlator is a difference between in- and out-of-plane quantities.

The first measurement of the CME correlator was performed by the STAR Collaboration [7] in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, and revealed a non-zero signal. Following that, the ALICE Collaboration made a comparable measurement in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [8]. The two results are striking in that the correlator strength was almost identical at the two energies. Based on simple expectations from the life time of the magnetic field, which is much shorter at the LHC, the correlation strength was expected to be smaller. Conversely, the radial and anisotropic flow are comparable between the two, suggesting that if any CME were present, it could be subdominant to background correlations. However, it has also been observed that, in the presence of an electrically conducting medium, the field lifetime could be extended considerably [9]. This could plausibly allow the correlation strength from the CME to be similar at different heavy ion collision energies.

More recently, it has been observed by the STAR Collaboration [10] that the charge dependence of v_1 measured in asymmetric Cu+Au collisions, where there is a strong electric field pointing in the direction of the impact parameter, indicates that the percentage of quarks present at early times while the fields are still strong is only about 10%, which places constraints on the CME.

Very recently, the CMS Collaboration [1] has presented the first measurement of the CME correlator in p+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, and shown them to be remarkably consistent with the results in Pb+Pb at $\sqrt{s_{NN}}$ = 5.02 TeV at the same particle multiplicity. Given that naively one expects no CME in p+Pb collisions, this places the strongest constraints yet on the level of CME that can contribute to the observed correlations. However, the argument they present that one expects no CME in p+Pb hinges on two postulates: firstly, that the magnetic field in p+Pb collisions is smaller than that in Pb+Pb; and secondly that the magnetic field is uncorrelated with the flow plane angle ψ_2. In this paper we test these two postulates.

II. MONTE CARLO GLAUBER AND MAGNETIC FIELD CALCULATION

A detailed calculation of the spatial and temporal dependence of the magnetic field present in heavy ion collisions and its interaction with the quarks when present can be complicated. However, in this case we want to compare the relative magnetic field magnitude at the initial collision time in the participant region and its orientation between Pb+Pb and p+Pb interactions. For this purpose, we utilize a modified version of the Monte Carlo Glauber code as detailed in Ref. [11].

We use the standard Woods-Saxon parameters for the Pb nucleus in distributing the nucleons, including a hard-core repulsive interaction (i.e. nucleons are required to be at least $d > 0.4$ fm apart based on their center positions). We assume that the distribution of protons and neutrons are given by the same function (i.e. no neutron skin is considered). For each event, we utilize a nucleon-nucleon inelastic cross section of 60 millibarns and determine if nucleons interact in the black disk picture. For each Pb+Pb or p+Pb event, we determine the center-of-mass of the participating nucleons, defined as nucleons with at least one interaction. We then calculate the magnitude (ε_2) and angle (ψ_2) of the eccentricity by

$$\varepsilon_2 = \frac{\sqrt{\langle r^2 \cos(2\phi)\rangle^2 + \langle r^2 \sin(2\phi)\rangle^2}}{\langle r^2 \rangle}, \tag{5}$$

$$\psi_2 = \frac{\mathrm{atan2}\left(\left\langle r^2 \sin(2\phi)\right\rangle, \left\langle r^2 \cos(2\phi)\right\rangle\right)}{2} + \frac{\pi}{2}, \tag{6}$$

where r is the displacement of the participating nucleon from the center-of-mass, ϕ is the angle of the participating nucleon in the transverse plane, and the brackets indicate an average over all participants.

In this manuscript we calculate only the peak field strength, i.e. the field strength at the time of impact. In Ref. [12], they use a dynamical model to calculate the time dependence of the field strength. The field strength they determine at $t = 0$ is consistent with our calculations. Relatedly, the same model for the time evolution of the fields can be used to evaluate possible background contributions to the three-point correlator [13].

One example Pb+Pb peripheral event is shown in the left panel of Figure 1 in the transverse plane. The gray open circles are the nucleon spectators from both nuclei. The left nucleus is moving out of the page, as indicated by the dots in the center of the circles. The right nucleus is moving into the page, as indicated by the crosses in the center of the circles. The green (red) filled circles indicate participating nucleons moving out (into) the page. The black arrow indicates the orientation of the eccentricity along the long axis and is drawn from the center-of-mass of the participating nucleons.

The magnetic field is calculated specifically at the center-of-mass position of the participating nucleons. We assume a Gaussian spatial distribution with $\sigma = 0.4$ fm

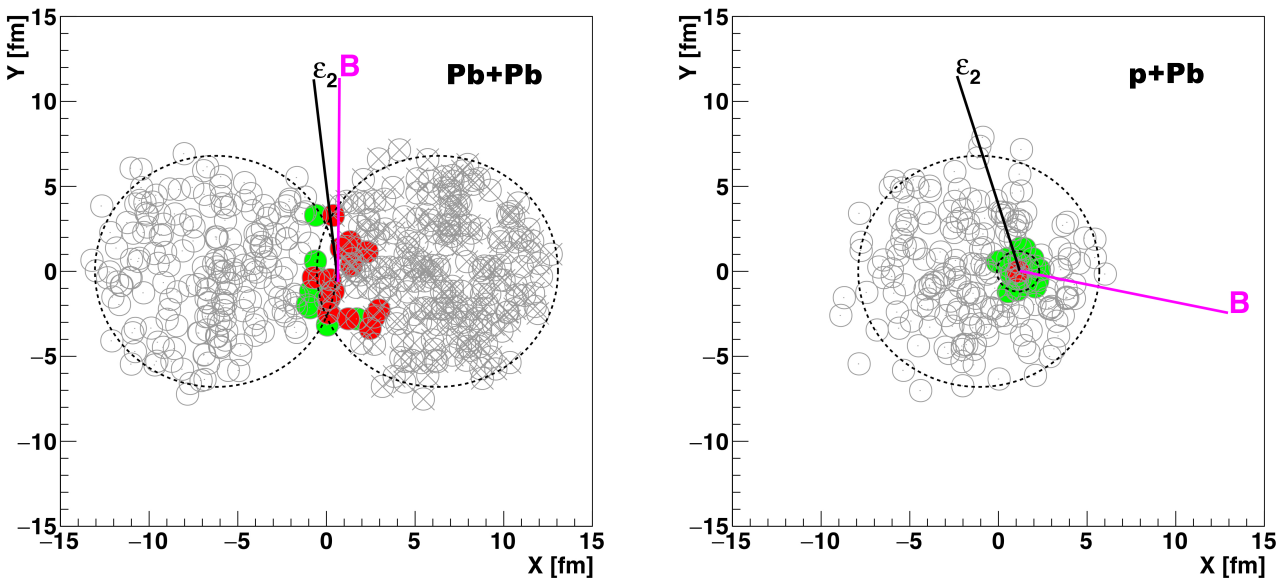

FIG. 1. Single event display from an Monte Carlo Glauber event of a peripheral Pb+Pb (left panel) and a central p+Pb (right panel) collision at 5.02 TeV. The open gray (filled green) circles indicate spectator nucleons (participating protons) traveling in the positive z-direction, and the open gray (filled red) circles with crosses indicate spectator nucleons (participating protons) traveling in the negative z-direction. In each panel, the calculated magnetic field vector is shown as a solid magenta line and the long axis of the participant eccentricity is shown as a solid black line.

for the distribution of the electric charge for each proton. We note that following the procedure in Ref. [14], we checked the calculation results using a point charge at the center of each proton and excluding protons with $r < 0.3$ fm of the point where the field is determined, and found similar results in all cases. To determine the magnetic field, we use the Biot-Savart law for moving point charges:

$$\vec{E} = \frac{q}{4\pi\varepsilon_0}\frac{1-v^2/c^2}{(1-v^2\sin^2\theta/c^2)^{3/2}}\frac{\hat{r}'}{\vec{r}^2}, \quad (7)$$

$$\vec{B} = \frac{1}{c^2}\vec{v}\times\vec{E}, \quad (8)$$

where $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, q is the charge of the proton, ε_0 is the electric permitivity of free space, v is the velocity of the proton, c is the speed of light, $\vec{r}$ is the displacement between the proton and the center-of-mass of the participating nucleons, and θ is the angle between the velocity vector and the displacement vector, which is exactly 90° at the moment of impact of the two colliding nuclei. The vector direction of the magnetic field is shown in the example Pb+Pb interaction in the left panel of Figure 1.

In this particular event, the magnetic field is oriented upwards, which is the expectation in the absence of fluctuations in the positions of the protons. It is also true in this one event that the long axis of the eccentricity is aligned closely with the magnetic field. Thus, for this event, there is a significant magnetic field along this long axis and a very small magnetic field perpendicular to it. This is the type of configuration that makes the CME maximally observable with the three-point correlator.

We show in the right panel of Figure 1 an example p+Pb interaction where we again calculate the long axis of the eccentricity and magnetic field vector in the identical framework. In this example interaction, the magnetic field and eccentricity long axis are almost perpendicular. In addition, the magnetic field vector itself, due to fluctuations in the positions of the protons (particularly those closest to the participant center-of-mass), is not along the expected direction (i.e. expected for the case of a smooth charge distributed nucleus).

III. RESULTS

In order to fully quantify these effects, we sample over one million Pb+Pb and one million p+Pb Monte Carlo Glauber events. First, we discuss the Pb+Pb results. In Figure 2, the left panel shows the mean of the absolute value of the magnetic field oriented along the x-axis $\langle|B_x|\rangle$ (open circles) and the y-axis $\langle|B_y|\rangle$ (open squares) as a function of the Pb+Pb collision impact parameter. Note that the impact parameter vector is always along the x-axis. The magnetic field is shown in units of Tesla. Commonly in the literature the quantity $\hbar eB/c^2$ is reported, which gives an equivalence 10^{15} T $\leftrightarrow$ 3.0366 m_π^2, where m_π is the mass of the charged pion (139.57 MeV/c^2).

As expected, in peripheral Pb+Pb events, there is a large mean magnetic field oriented in the y-direction, and a rather small mean magnetic field oriented in the x-direction. Note that if we did not calculate the mean of the absolute value, the mean magnetic field in the x-direction would be zero with as many events fluctuating to have a positive and negative field along this axis. In the most central (b close to zero) events, the two magnetic field components have equal mean values since the magnetic field is entirely due to fluctuations in the proton positions. In the right panel, we show the same result, now as a function of the number of participating nucleons, which is related to the number of particles produced in the event.

In addition, in the right panel of Figure 2, we show the magnetic field mean values now oriented along the long axis of the eccentricity (shown as a black arrow labeled ε_2 in Figure 1), referred to as $\langle|B'_y|\rangle$, and in the perpendicular direction, referred to as $\langle|B'_x|\rangle$. It is striking that due to significant fluctuations in the orientation of the eccentricity and the magnetic field direction, there is a substantial $\langle|B'_x|\rangle$ component. However, the potential for the three-point correlator to measure the CME remains, as the two components are still significantly different (the mean absolute value $\langle|B'_y|\rangle \approx 1.5 \times \langle|B'_x|\rangle$).

Figure 3 shows the same quantities but now for p+Pb collisions. Two clear conclusions can be reached. First, the magnetic field mean absolute values are not small. In fact, the magnetic field magnitudes in the rotated frame are comparable to the Pb+Pb x' component and only about 50% smaller than the y' component. The average impact parameter even in the large number of participating nucleon events is of order 1.5-1.7 fm (still non-zero) and the fluctuations in the nearest protons to the participant center-of-mass generate significant fields.

More importantly, the second conclusion is that for p+Pb collisions, the magnetic field direction and the eccentricity orientation are uncorrelated so that one finds that $\langle|B'_y|\rangle = \langle|B'_x|\rangle$. This confirms the second postulate in the CMS paper, and gives the strong conclusion that the CME must not be the effect being observed in the three-point correlator in p+Pb interactions. Given the similarity of the p+Pb and Pb+Pb experimental results, it is also unlikely that the Pb+Pb are the result of the CME.

Figure 4 shows the same quantities but now for d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV; note that the arbitrary scale is different from that of Figures 2 and 3. The exact same conclusions about the magnetic field in p+Pb can be drawn about that in d+Au. The study of this correlator in small systems at RHIC energies should be elucidating. We note that in 2016 d+Au data was taken at collision energies 200, 62.4, 39, and 19.6 GeV.

It is notable that even in Pb+Pb semi-central collisions, where the average magnetic field and the flow vector retain a correlation, the magnetic field is highly inhomogeneous. The left panel of Figure 5 shows a single Pb+Pb collision, where the color scale in log z shows the magnitude of the magnetic field as a map in transverse position space. The arrows indicate the direction of the magnetic field in each spatial cell. The preponderance of red color in the overlap region and lighter colors away from there is qualitatively consistent with general expectations. On the other hand, the field directions do have significant fluctuations away from the average in the overlap region, indicating a large degree of inhomogeneity. In order to quantify the inhomogeneity, we examine Pb+Pb collisions with $75 < N_{part} < 100$, averaging over an ensemble of events. We compute the component of the magnetic field along the flow vector ($|B'_y|$) at two positions: 1 fm above the center of mass and 1 fm below the center of mass. We then compute the ratio of these two values with the larger magnitude number always in the denominator. A positive value indicates the components along the flow vector are in the same direction; a negative value indicates the components are in opposite directions. This quantity is shown in the right panel of Figure 5. Approximately 20% of the time, the components are in the opposite direction whereas they are in the same direction about 80% of the time. However, even when the components are in the same direction, the value of the smaller of two is about half that of the larger. Any calculation of the CME should take into consideration the inhomogeneities of the magnetic field, which have roughly the same size scale as the topological domains.

IV. SUMMARY AND OUTLOOK

The impact of the CMS result is clear. As we have demonstrated in this paper, the magnetic field direction in p+Pb collisions is uncorrelated with the flow angle, and therefore the CME cannot contribute any signal to the observed correlations. Considering the remarkable similarity between the p+Pb and Pb+Pb measurements, any CME contribution to the observed heavy ion collisions at the LHC must be heavily subdominant. While the case is likely quite different at RHIC, where the magnetic field is weaker but much longer lived, the similarity between the centrality dependence LHC and RHIC results discussed earlier remains an important open question. Because the CME is subdominant to a mimic signal, a much higher burden of proof is required for validation. The theory behind the CME is extremely strong. The physics of the $U(1)_A$ anomaly in QCD is very well established and very clear. If we had an arbitrarily long-lived quark gluon plasma and could embed it in an arbitrarily strong and long-lived magnetic field, there is essentially no question that the CME would occur. Indeed, there is an analogous effect in QED (to wit, the axial anomaly in QED allows the neutral pion to decay into two photons), which has not only been predicted but observed [15]. Regrettably, the quark gluon plasma we can create in the lab has relatively short life time, and the magnetic field induced is the strongest magnetic field observed anywhere in the universe but also extremely short

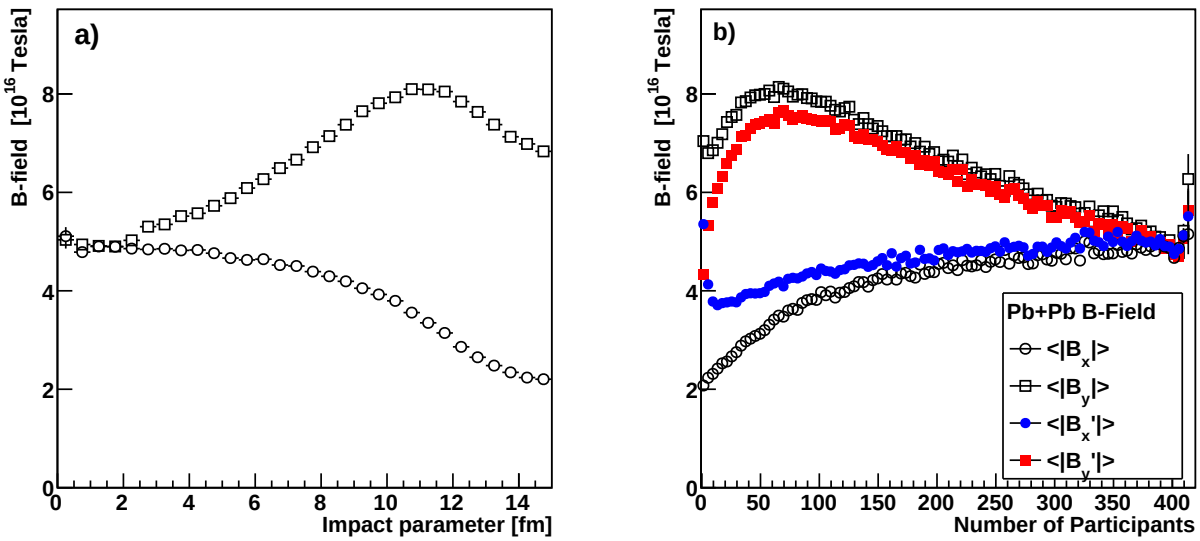

FIG. 2. Magnetic field components parallel ($|B_x|$, indicated by black open circles) and perpendicular ($|B_y|$, black open squares) to the impact parameter vector as a function of impact parameter (left panel) and N_{part} (right panel) in Pb+Pb collisions. The filled red squares on the right panel indicate the rotated components parallel to the eccentricity direction ($|B'_x|$) and the filled blue circles rotated component perpendicular to the eccentricity direction ($|B'_y|$).

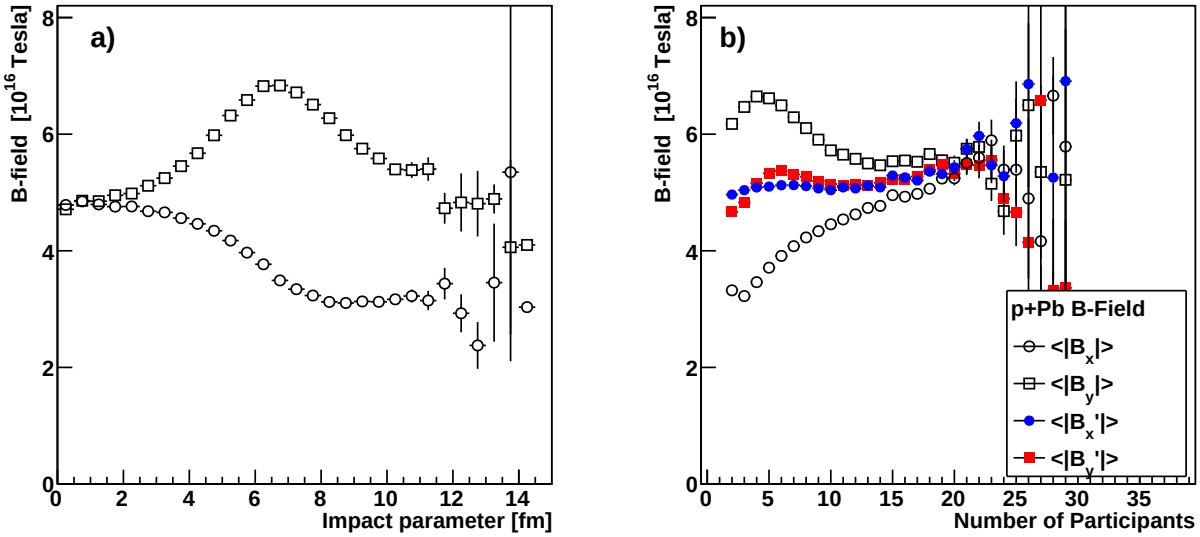

FIG. 3. Magnetic field components parallel ($|B_x|$, indicated by black open circles) and perpendicular ($|B_y|$, black open squares) to the impact parameter vector as a function of impact parameter (left panel) and N_{part} (right panel) in p+Pb collisions. The filled red squares on the right panel indicate the rotated components parallel to the eccentricity direction ($|B'_x|$) and the filled blue circles rotated component perpendicular to the eccentricity direction ($|B'_y|$).

lived. However, while it is clear that the CME must be heavily subdominant to the observed correlations, there is still the possibility that sufficiently advanced detectors and techniques can observe it. As Eugene Wigner once said, the optimist regards the future as uncertain.

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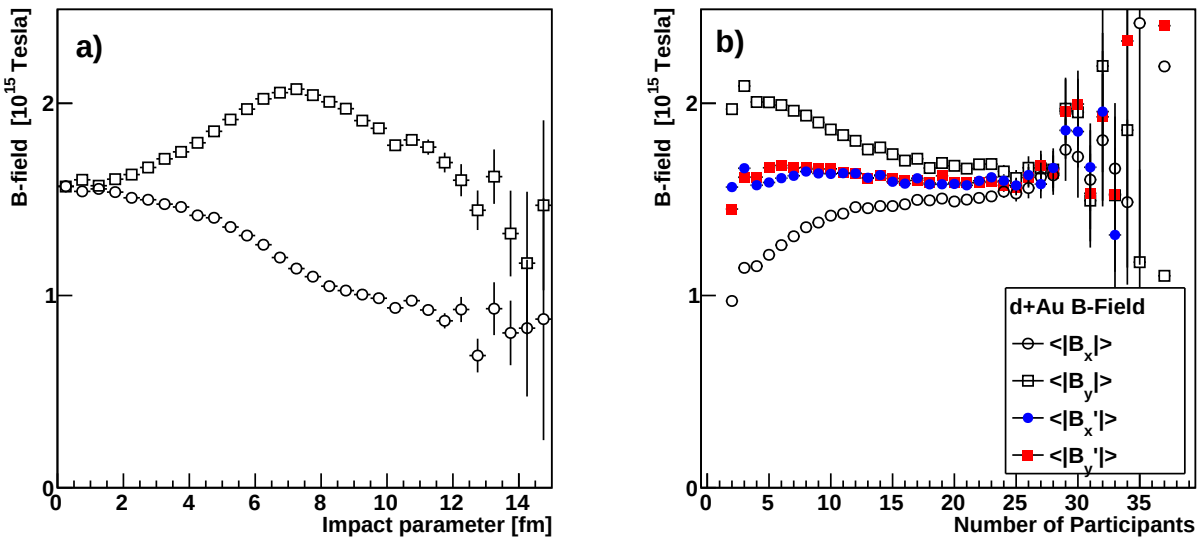

FIG. 4. Magnetic field components parallel ($|B_x|$, indicated by black open circles) and perpendicular ($|B_y|$, black open squares) to the impact parameter vector as a function of impact parameter (left panel) and N_{part} (right panel) in d+Au collisions. The filled red squares on the right panel indicate the rotated components parallel to the eccentricity direction ($|B'_x|$) and the filled blue circles rotated component perpendicular to the eccentricity direction ($|B'_y|$).

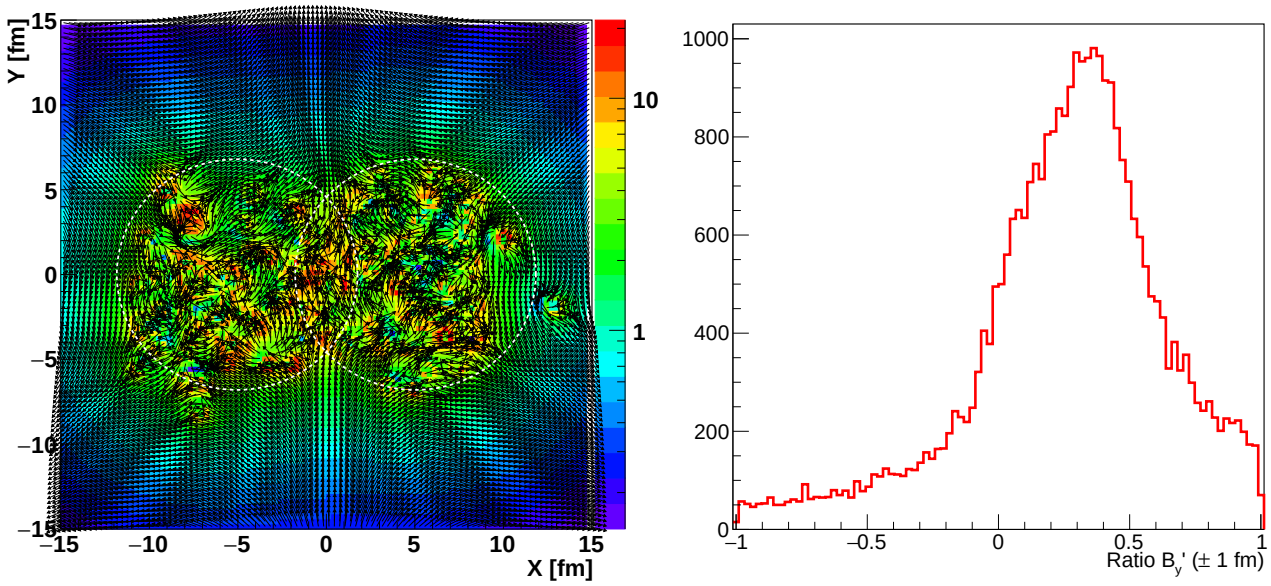

FIG. 5. (Left panel) Magnetic field map in a peripheral Pb+Pb collisions, where the color indicates the field strength and the arrow indicates the direction. The preponderence of more red colors in the overlap zone indicates a stronger magnetic field in that area. (Right panel) Ratio of magnetic field component perpendicular to the eccentricity direction ($|B'_y|$) at one point and at another point 1 fm away along the same direction. A positive value indicates the fields at the two points are aligned, a negative value indicates the fields are anti-aligned.

[1] V. Khachatryan *et al.* (CMS), Phys. Rev. Lett. **118**, 122301 (2017).

[2] D. E. Kharzeev, Ann. Rev. Nucl. Part. Sci. **65**, 193 (2015).

[3] D. E. Kharzeev, J. Liao, S. A. Voloshin, and G. Wang, Prog. Part. Nucl. Phys. **88**, 1 (2016).
[4] S. Voloshin and Y. Zhang, Z.Phys. **C70**, 665 (1996).
[5] S. A. Voloshin, Phys.Rev. **C70**, 057901 (2004).
[6] B. Alver *et al.* (PHOBOS), Phys. Rev. Lett. **98**, 242302 (2007).
[7] B. I. Abelev *et al.* (STAR), Phys. Rev. **C81**, 054908 (2010).
[8] B. Abelev *et al.* (ALICE), Phys. Rev. Lett. **110**, 012301 (2013).
[9] L. McLerran and V. Skokov, Nucl.Phys. **A929**, 184 (2014).
[10] L. Adamczyk *et al.* (STAR), (2016).
[11] C. Loizides, J. Nagle, and P. Steinberg, SoftwareX **1-2**, 13 (2015).
[12] V. Voronyuk, V. D. Toneev, W. Cassing, E. L. Bratkovskaya, V. P. Konchakovski, and S. A. Voloshin, Phys. Rev. **C83**, 054911 (2011).
[13] V. D. Toneev, V. P. Konchakovski, V. Voronyuk, E. L. Bratkovskaya, and W. Cassing, Phys. Rev. **C86**, 064907 (2012).
[14] A. Bzdak and V. Skokov, Phys. Lett. **B710**, 171 (2012).
[15] Q. Li, D. E. Kharzeev, C. Zhang, Y. Huang, I. Pletikosic, A. V. Fedorov, R. D. Zhong, J. A. Schneeloch, G. D. Gu, and T. Valla, Nature Phys. **12**, 550 (2016).