Estimation of $\mathcal{P}$-odd correlators in heavy ion collisions at RHIC energies 62.4 – 200 GeV

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The strength of parity violation effect can be characterized by correlator value in the framework of local $\mathcal{TIP}$ hypothesis. The energy and centrality dependencies of correlators for same and opposite charges are discussed for heavy ion collisions in RHIC energy domain 62.4 – 200 GeV. The magnetic field shows a significant increasing at initial energy decreasing for intermediate and large times. Two possible scenarios for initial time are investigated in detail. Both scenarios predict the most close values for initial time in Au+Au collisions at 62.4 GeV. Disagreement between initial time values obtained for two various scenarios increases with energy increasing and for collisions of lighter Cu-nucleus. Boundary values for correlators related with possible local $\mathcal{TIP}$ violation are calculated in the framework of analytic approach of chiral magnetic effect for Au+Au collisions at 62.4 and 200 GeV. The results are shown as function of collision centrality. Preliminary experimental STAR data are compared with predictions of chiral magnetic effect model directly. Experimental signals consistent with model expectations for both same and opposite charge correlations in Au+Au collisions at 62.4 GeV at all centralities. At higher energy 200 GeV the model of chiral magnetic effect underestimates same charge correlator values for central and midcentral events but the same charge correlations for peripheral events as well as opposite charge correlations are in the boundaries predicted by model calculations.

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I. INTRODUCTION

Quantum chromodynamics (QCD) as non-Abelian gauge theory contains non-trivial topological field configurations which deeply relate with $\mathcal{P}/\mathcal{C}\mathcal{P}$ invariance of strong interactions. The non-trivial topology of QCD vacuum opens the possibility for existence of metastable $\mathcal{P}$ and $\mathcal{C}\mathcal{P}$ odd domains. The possibility of such domains was inferred both from analysis of an effective chiral theory incorporating axial anomaly [1] and from study of space-time regions occupied by gauge filed configurations with non-trivial topological charge [2, 3]. These domains can lead to $\mathcal{P}$ and $\mathcal{C}\mathcal{P}$ violation in strong interactions for some local space region in the vicinity of the deconfinement phase transition, i.e induce the local strong parity violation effect. Because topology origin this effect can be assigned also as local topology induced parity violation ($\mathcal{TIP}$) effect. It was suggested in [1] that metastable $\mathcal{P}$ and $\mathcal{C}\mathcal{P}$ odd domains might be created in heavy ion collisions at high energies. The mechanism by which such domains can demonstrate themselves, in particular, via separate electric charges in the presence of a background strong magnetic field – the chiral magnetic effect – was suggested in [3]. The effect predicts the preferential emission of charged particles along the direction of system's angular momentum in the case of the noncentral heavy-ion collisions due to the presence of nonzero chirality. Since separation of charge is $\mathcal{C}\mathcal{P}$ odd, any experimental observations of the chiral magnetic effect could be provided a clear demonstration of the non-trivial topological structure of the QCD vacuum. Moreover the key requires for the possible local $\mathcal{TIP}$ violation in strong interactions are the deconfinement state of matter with restored chiral symmetry [2, 4]. The former is needed to separate (anti-)quarks with opposite electric charges by a distance larger than nucleon size. The spatially restored chiral symmetry is required because charge separation is possible at conserved chirality only. Thus the positive and reliable experimental results for $\mathcal{P}$ and $\mathcal{C}\mathcal{P}$ violation in the strong interactions would be prove the clear evidence of deconfinement and chirally symmetric phase creation and establish experimentally the existence of non-trivial topological field configurations in QCD and their role in chiral symmetry breaking [2, 5]. Possible experimental signals of local parity violation in relativistic heavy ion collisions were suggested in [2, 10]. It was suggested that signals of local $\mathcal{TIP}$ violation in heavy ion collisions can be observed through the e-by-e charge assymetries with respect to the reaction plane. The energy dependence of strength of the local $\mathcal{TIP}$ violation is important challenge for study of various phases and critical point for strongly interacting matter.

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II. METHOD

The averaged correlators for chiral magnetic effect approach are defined as \[ a_{\pm} = \frac{1}{N_{\pm}^2} \pi^2 \int_0^{\pi} g(b/R, \lambda/R) \Phi(b/R, \tau, \eta) \, d\tau \, d\eta, \quad a_{+} = -\frac{1}{N_+ N_-} \pi^2 \int_0^{\pi/2} h(b/R, \lambda/R) \Phi(b/R, \tau, \eta) \, d\tau \, d\eta. \tag{1} \]

for same and opposite charges respectively, where \( N_{\pm} \) denotes the total number of charged particles in the corresponding pseudorapidity interval. The function \( \Phi(b/R, \tau, \eta) \) is following

\[
\Phi(b/R, \tau, \eta) = 4 \kappa \alpha_b R^2 \left[ \sum_j q_j^2 \right]^2 \int_{\tau_i}^{\tau_f} d\tau \tau \left[ eB(\tau, \eta) \right]^2.
\tag{2}
\]

Here the proper time \( \tau = \sqrt{t^2 - z^2} \) and space-time rapidity \( \eta = 0.5 \ln \left[ (t + z)/(t - z) \right] \). The time integral on magnetic field is from initial time \( \tau_i \) to a final time \( \tau_f \). The \( g(b/R, \lambda/R), h(b/R, \lambda/R) \) are some universal functions which depend on centrality \( (b/R) \) and screening length \( (\lambda) \), which is assumed a constant in time range for integral. Here \( \alpha_b \) is strong coupling constant, \( R \) - nucleus radius, \( \kappa \sim 1 \) is a some constant coefficient, \( q_j \) is the charge in units of \( e \) of a quark with flavor \( j \). This approach is valid for a constant homogeneous magnetic field. In the overlap region the magnetic field is to a good degree homogenous around zero space-time rapidity especially for large impact parameters. The more detail description is in \[ 3 \].

In the energy domain under study the Lorentz contraction factor \( \gamma_L \) of colliding nuclei is in 31.2 – 100 range. Hence the nuclei are Lorentz contracted in the \( z \)-direction to about 3 (1) percent of their original size for collision energy 62.4 (200) GeV. Therefore the pancake shape seems valid approximation for two colliding nuclei. One can assume \( \tau_f \) is infinity in the \[ 2 \] because of dependence of magnetic field absolute value on \( \tau \) shows the rapid decreasing of \( (eB) \) with \( \tau \) increasing \[ 3 \]. Analytic approach for magnetic field from \[ 3 \] allows us to redefine the \[ 2 \] and derive the following analytic formula:

\[
\Phi(b/R, \tau_i, Y_0) = 4 \kappa \alpha_b (Z \alpha_{EM})^2 \left[ \sum_j q_j^2 \right]^2 \frac{R_{\tau_i}}{R_{\tau_f}} e^{-Y_0} \left[ c^2 f^2 \left( \frac{b}{R} \right) + \frac{32}{5} c f \left( \frac{b}{R} \right) \frac{b}{R} \frac{\sqrt{N}}{\tau_i^{3/2}} e^{-3Y_0/2} + \frac{b^2 R}{\tau_i} e^{-3Y_0} \right], \tag{3}
\]

where \( c \approx 0.599, \alpha_{EM} \) denotes the electromagnetic fine structure constant, \( f(b/R) \) is some universal function which depends on centrality, and \( Y_0 \) - the beam rapidity. The analytic approach for magnetic field and, as consequence, formula \[ 3 \] are valid for \( R/\sinh(Y_0) \ll \tau \ll R \). Thus correlator values depend on \( \tau \), choice, beam characteristics (ion type and initial energy), and centrality in the 2D approach with sharp boundary of surface for density of incoming nuclei.

Experimental observation of charge separation effect is possible only by correlation techniques because of direction of charge separation may change event by event due to random sign of the topological charge of the local domain. The \( P \)-even experimental observable which is sensitive to the charge separation relates with averaged correlator from chiral magnetic effect model as following \[ 11 \]:

\[
\langle \cos (\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle - \langle B_{in} - B_{out} \rangle - \langle v_{0}^\alpha v_{1}\beta \rangle = -\langle a_\alpha a_\beta \rangle, \tag{4}
\]

where \( \alpha, \beta = -, + \) denote the particle electric charges, \( \Psi_{RP} \) - azimuthal angle of the reaction plane, \( v_1 \) - directed flow parameter. The average in \[ 3 \] is taken over all pairs in some event and then over all events with given centrality. The experimentally measured correlator \( \langle \cos (\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \) represents the difference between correlations projected onto an axis in the reaction plane and the correlations projected onto an axis perpendicular to the reaction plane. The important advantage of using \[ 4 \] is that it removes all the correlations among particles \( \alpha \) and \( \beta \) that are not related to the reaction plane orientation \[ 12, 13 \]. The second term on the left side is the difference between background contribution of the in-plane correlations \( B_{in} \) and background contribution of the out-of-plane correlations \( B_{out} \). Note that the contribution given by the term \( \langle v_{0}^\alpha v_{1}\beta \rangle \) be neglected because directed flow averages to zero in a rapidity region symmetric with respect to midrapidity region which is considered in this paper \[ 13, 14 \].

III. RESULTS

We consider the magnetic fields created in non-central heavy-ion collisions for two different beams in the framework of analytic approach of chiral magnetic effect at \( R/\sinh(Y_0) \ll \tau \[ 3 \]. The ratio of magnetic fields created in various
collisions, \( \xi = (eB)_1 / (eB)_2 \) is investigated here in dependence on proper time. Fig.1 shows the \( \xi \) for two different RHIC beam types at equal collision energies and the ratio of strengths of magnetic fields created by Au beams at various energies is presented at Fig.2. Magnetic field is larger for more heavy nucleus at any energies as expected and magnetic field value is more sensitive to beam energy than beam ion type. First estimates for \( \xi \) at low energies \( \sqrt{s_{NN}} < 20 \text{ GeV} \) were obtained also in pancake approach with sharp surface boundary [15]. In this analytic approach the magnetic field at intermediate energies is larger significantly than that for high energy domain. It should be stressed additionally that 2D pancake picture is rough approach for low energy domain. Thus the magnetic field value decreases more rapidly for higher energies at intermediate and large \( \tau \). The recent UrQMD calculations [16] show magnitude of magnetic field \( (eB)_y \sim m_\pi^2 \) for Au+Au collisions at at highest RHIC energy \( \sqrt{s_{NN}} = 200 \text{ GeV} \). This estimation is similar to the magnitude calculated in the framework of chiral magnetic effect model. The UrQMD model as well as numerical estimations for chiral magnetic effect shows the increasing of strength of background magnetic field with initial energy increasing at very small times \( R/\sinh(Y_0) \gtrsim \tau \).

As seen from (3) expressions for variations of the difference between the number of raising and lowering transitions depend on the choice of the initial time [3]. In the framework of analytic approach for chiral magnetic effect two possible scenarios for initial time definition were suggested. If the time at which the topological charge changing processes is less than the Lorentz contracted size of the system, one can use the Lorentz contracted size scale for estimation of up limit of initial time: \( \tau_{II}^i = \zeta R \exp(-Y_0) \), where \( \zeta \simeq 2 \). On the other hand, if the time at which the topological charge changing processes is larger than the Lorentz contracted size of the system, we should use the following scale for estimation of initial time: \( \tau_{III}^i \sim 1/Q_{\text{sat}} \), here \( Q_{\text{sat}} \) is the saturation scale [3]. As seen the \( \tau_{III}^i \) depends on centrality and beam type due to \( Q_{\text{sat}} \). These scenarios define the boundary values for initial time. Thus correlator values calculated for \( \tau_{II}^i \) and \( \tau_{III}^i \) are limit values for certain kinematics and beam type. Fig.3 shows energy dependence of initial time at various scenarios for Cu (Fig.3a) and for Au (Fig.3b) beams.

Ratio of initial time values derived from scenarios under study is demonstrated on the Fig.4 for two RHIC energies and various beam types. One needs to emphasize that both scenarios for initial time show the similar values up to order of magnitude, at least, for RHIC energy domain 62.4 - 200 GeV. Two scenarios agree well especially at 62.4 GeV for central and midcentral collisions and all nuclei under study. The differences between these scenarios are significantly larger for lower and higher collision energies. Therefore one can expect wider allowed domain for correlator values at lower and higher initial energies than that for RHIC ones.

Thus it should be stressed the unique situation for RHIC energy domain 62.4 - 200 GeV: (i) the pancake shape is a really good approximation and one can consider 2D picture for magnetic field calculation; (ii) the two various
scenarios for initial time result in a similar estimations.

The important feature of (3) is the dependencies of Φ function (and, as consequence, correlators too) on beam type and centrality only for choice of the first scenario for \( \tau_i \). Thus if the same colliding nuclei under study one can obtain the simple relations for correlators at two various initial energies \( \sqrt{s_1} \) and \( \sqrt{s_2} \):

\[
\frac{a_{\pm\pm}\sqrt{s_1}}{a_{\pm\pm}\sqrt{s_2}} = \left[ \frac{N_{\pm}\sqrt{s_2}}{N_{\pm}\sqrt{s_1}} \right]^2, \quad \frac{a_{\pm-}\sqrt{s_1}}{a_{\pm-}\sqrt{s_2}} = \left[ \frac{N_{+}N_{-}\sqrt{s_2}}{N_{+}N_{-}\sqrt{s_1}} \right].
\]  

(5)

Based on the (5) and energy dependence of charged particle multiplicity in heavy ion collisions [17] one can obtain

\[
\frac{a_{\pm\pm}\mid_{200}}{a_{\pm\pm}\mid_{62.4}} = \frac{a_{\pm-}\mid_{200}}{a_{\pm-}\mid_{62.4}} \approx 0.527.
\]

The estimations for correlators \( a_{\pm} \) and \( |a_{\pm-}| \) for Au+Au collisions at \( \sqrt{s_{NN}} = 130 \text{ GeV} \) were calculated in [3]. The centrality dependence of correlator values for Au+Au at 62.4 GeV and 200 GeV are shown at Fig.5 for same (a,b) and opposite (b,d) charge combinations for Lorentz contracted scale (a,c) and saturation scale (b,d) scenarios for initial time. We have assumed \( N_{+} \approx N_{-} \approx N_{ch}/2 \) and \( \lambda = 1 \text{ fm} \) [3], where \( N_{ch} \) is the charged particle multiplicity at midrapidity for centrality bin under consideration. As expected above both correlators show a fast increasing at decreasing of collision centrality for \( \tau_i^1 \) scenario (Fig.5a,c). Correlator estimations in the framework of saturation scale scenario show a slow increasing at decreasing of collision centrality and decreasing for most peripheral collisions both for same (Fig.5b) and opposite (Fig.5d) charge combinations. But it should be stressed that saturation scale calculations based on the approach from [17] and available data allow us to make an approximate and rough estimations for \( Q_{sat} \) for two most peripheral centrality bins. Saturation scenario for \( \tau_i \) results in significantly smaller values both for same and opposite charge correlators for midcentral and peripheral events than correlator estimations at \( \tau_i^1 \). It seems the decreasing of correlators for most peripheral bin is more reasonable than that behaviour in the framework of the first scenario for \( \tau_i \) because the deconfinement matter is created in (mid-)central collisions. Thus the analytic approach for observables related with possible local TIP violation allows us to get limit values for same and opposite charge correlators. Direct comparison of expectation values for correlators calculated in the framework of local TIP...
hypothesis and preliminary experimental STAR data [14] are shown at Fig.4 and Fig.7 for collision energies 62.4 GeV and 200 GeV, respectively. The contribution given by the term from directed flow in (4) is assumed equal zero for experimental data [14]. Preliminary STAR data are in the ranges predicted by analytic approach for chiral magnetic effect for opposite charge correlations at overall centralities and both energies under consideration. Model values calculated for the $\tau_1$ scenario are very close to the preliminary experimental results for opposite charge combinations. In contrast, the same charge experimental correlations are within model boundaries for 62.4 GeV at most of centrality bins and for peripheral bins for 200 GeV. But the model predicts very wide allowed range in the last case. Thus agreement between experimental data and model estimations is better for lower energy.

Perhaps disagreement between preliminary experimental data and model estimations at 200 GeV for central and midcentral collisions can be explained by significant difference between background contributions of in-plane correlations and out-of-plane correlations: power of jet quenching, for example, depends on orientation with respect to the reaction plane [18, 19]. This can leads to the increasing of $\Delta B = B_{in} - B_{out}$. One can expect that the difference between contributions of jet-like in-plane correlations and out-of-plane correlations decreases with energy decreasing. Thus the disbalance $\Delta B$ is lower for lower energy. On the other hand the exception of the very small times $R/\sinh(Y_0) \gtrsim \tau$ in present analytic approach may be one of the reasons for decreasing of calculated correlator estimations. It seems the influence of this exception is more significant at 200 GeV energy namely than at 62.4 GeV because larger magnitude at very small times and faster decreasing are expected for magnetic field at higher energy.

In addition one can get a rough estimations for $P$-odd correlators for first initial time scenario at LHC energy $\sqrt{s_{NN}} = 5.5$ TeV due to $R_{Au} \simeq R_{Pb}$. Thus

$$\frac{a_{\pm \pm}^{+\pm}_{LHC}}{a_{\pm \pm}^{+\pm}_{62.4}} \approx \frac{a_{\pm -}^{+\pm}_{LHC}}{a_{\pm -}^{+\pm}_{62.4}} \simeq 0.085$$

and interval estimations for same and opposite charge correlators are (from central to peripheral centrality bins) $a_{\pm \pm}^{+\pm}_{LHC} \sim [10^{-6} - 10^{-5}]$ and $a_{\pm -}^{+\pm}_{LHC} \sim [10^{-7} - 10^{-6}]$ by order of magnitude, respectively.

IV. SUMMARY

The background magnetic field shows a significant increasing at initial energy decreasing for intermediate and large times. Two scenarios for initial time give rise to values close to each other by order of magnitude in the RHIC energy domain 62.4–200 GeV. Boundary values of $P$-odd correlators are estimated for same and opposite charge combinations in Au+Au collision at 62.4 and 200 GeV. Preliminary STAR experimental data are compared with predictions of
FIG. 5: Centrality dependence of correlator absolute values for same (a,b) and opposite (c,d) charges in Au+Au collisions at RHIC energy domain 62.4 – 200 GeV in the framework of Lorentz contracted (a,c) and saturation (b,d) scale scenario for initial time. Data for 130 GeV are from [3].

Chiral magnetic effect model assumed local $\mathcal{TIP}$ violation at various centralities and collision energies. Centrality dependencies are similar for model results at first scenario of initial time and preliminary STAR experimental data at 62.4 and 200 GeV for both same and opposite charge correlators under consideration. Preliminary STAR data for Au+Au collisions at 62.4 GeV agree with allowed domain for correlator values from analytic approach of chiral magnetic effect for overall centralities reasonably. The model assumed local $\mathcal{TIP}$ violation underestimates correlator values for central events for Au+Au at 200 GeV. Agreement is some better for opposite charge correlators than that for same charge combination. Perhaps some disagreement at highest energy under consideration is explained by range of applicability of the analytic approach as well as some other effects which contribute in experimental results and not relate with local $\mathcal{TIP}$ violation hypothesis. The quantitative conclusions require, in particular, the additional study of behaviour of background magnetic field and more precise estimation of initial time for phenomenological calculations and future experimental investigation of this phenomenon.
FIG. 6: Centrality dependence for correlators calculated in the framework of analytic approach for chiral magnetic effect at two initial time scenarios and for preliminary experimental results obtained by STAR for charged particles in Au+Au collisions at 62.4 GeV [14].

FIG. 7: The correlators calculated in the framework of analytic approach for chiral magnetic effect at two initial time scenarios and preliminary experimental values obtained by STAR for charged particles in Au+Au collisions at 200 GeV [14] depend on collision centrality.

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