Charge-dependent azimuthal correlations of secondary particles in heavy ion collisions

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Abstract. The P/CP symmetry breaking in quantum chromodynamics (QCD) could be realized via transitions between local fluctuations of gauge fields. Azimuthal correlations which characterize the asymmetry of the emitted charged particles with respect to the reaction plane in non-central nucleus-nucleus collisions are the promising tools for experimental study of local P/CP violation in the strong interactions. The preliminary estimations of correlators within the model of chiral magnetic effect are presented for types of nuclei and collision energies corresponded to RHIC and the LHC beams for two various nuclear densities, namely, for approach of the hard sphere and for the two-component Fermi model. Besides of the correlator estimations for the symmetric collisions, the preliminary results for magnetic field in asymmetric $Cu+Au$ collisions are also shown.

1. Introduction

The Lagrangian of QCD contains natural terms that can break the P/CP symmetry [1]. There is a fundamental interrelation between geometry and fundamental properties of QCD Lagrangian. The vacuum of QCD is a very complicated matter with rich structure, which can corresponds to the fractal-like geometry [2]. The non-trivial topology of QCD vacuum opens the possibility for existence of metastable domains which possess of various properties with respect to the discrete P/CP symmetries. In the presence of background Abelian electromagnetic field decays of such domains or classical transitions (sphalerons) between them in deconfinement phase of color charges with restored chiral symmetry can lead to the separation of secondary charged particles toward the magnetic field. This phenomenon called also chiral magnetic effect (CME) is the experimental manifestation of the local topologically induced P/CP parity violation in the strong interactions [3].

2. Magnetic field in heavy-ion collisions

The magnetic field in nucleus-nucleus collisions can be obtained, for instance, using the Lienard–Wiechert potentials. This approach is described in detail elsewhere [3]. In the paper the strength of the magnetic field (eB) in collisions of various ion beams are compared for two parameterizations of nuclear density, namely, the sphere with sharp boundary, i.e. rigid sphere [3] and the following equation within the framework of two-component Fermi model

$$\rho_i^{\mathrm{F}}(\mathbf{x}'_\perp) = N_i^{\mathrm{F}}\varepsilon[1+\exp(-\varepsilon/a)]^{-1}\theta_i(\varepsilon^2), \quad \varepsilon \equiv \sqrt{R_i^2 - [\mathbf{x}'_\perp \pm \mathbf{b}/2 \mp (R_2^2-R_1^2)\mathbf{e}_\perp/2b]^2}, \qquad (1)$$

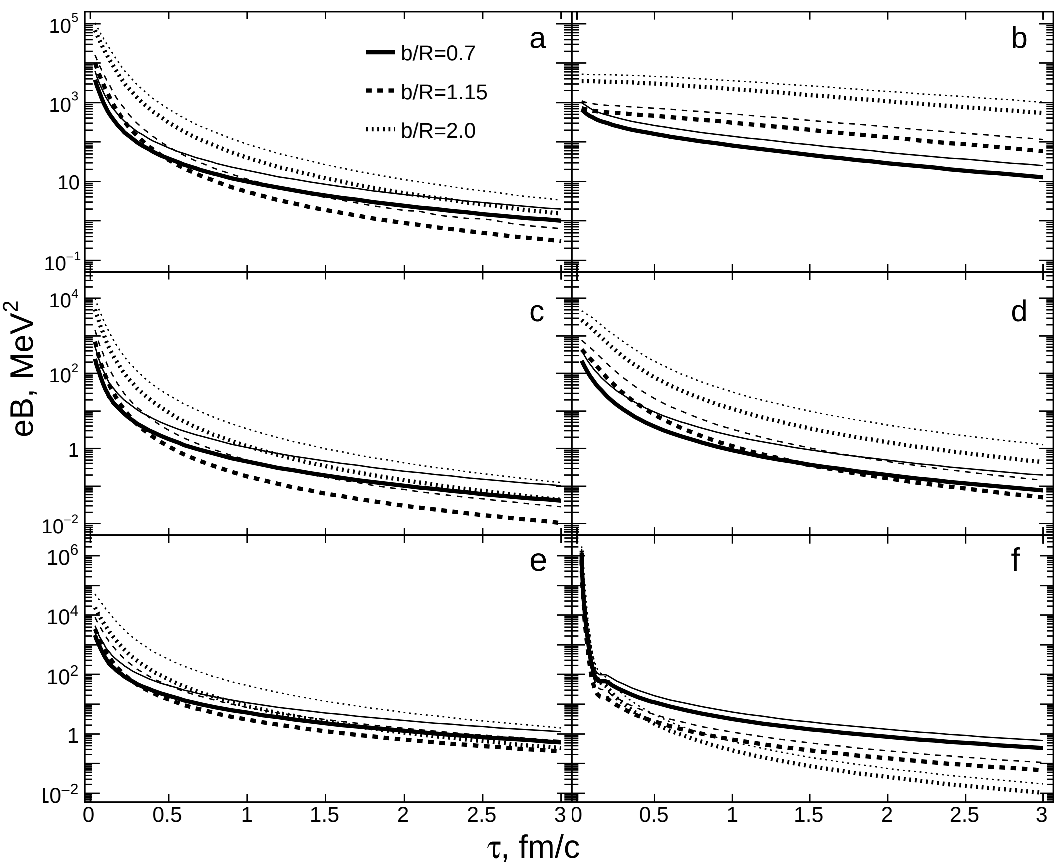

Figure 1. Dependence of the strength of magnetic field on proper time in nucleus-nucleus collisions at the origin ($x'_\perp = 0$) and central pseudorapidity ($\eta = 0$): $Au + Au$ at $\sqrt{s_{NN}} = 200$ (a) and 7.7 GeV (b); $Cu + Cu$ at $\sqrt{s_{NN}} = 200$(c) and 62.4 GeV (d); $Cu + Au$ at $\sqrt{s_{NN}} = 200$ GeV (e), $Pb + Pb$ at $\sqrt{s_{NN}} = 2.76$ TeV (f). The solid lines show $eB(\tau)$ for central collisions, dashed lines – for mid-central, dotted lines – for peripheral. Thin lines correspond to the limit case of the rigid sphere, thick lines – to the Fermi parametrization.

$$1/N_i^{\mathrm{F}} = 2\pi a \left\{ R_i^2 \ln(1+\kappa_i) + 2a \left[R_i \mathrm{Li}_2\left(-e^{\kappa_i}\right) - a\mathrm{Li}_3\left(-e^{\kappa_i}\right)\right] - 1.5a^2\zeta(3) \right\}.$$

Here b is the impact parameter, R_i – the radius of the nucleus moved along of the z-axis in the positive ($i = 1$) and negative ($i = 2$) directions, a is the cutoff factor, $\kappa_i \equiv R_i/a$, $\mathrm{Li}_j(x)$ and $\zeta(x)$ are the polylogarithm of j order and Riemann zeta function respectively, the nuclear densities are normalized such that $\int d\mathbf{x}'_\perp \, \rho_i^{\mathrm{F}}(\mathbf{x}'_\perp) = 1$ as well as in [3]. It would be stressed that the equation (2) is valid for asymmetric, in general case, nucleus-nucleus collisions. The strength of Abelian magnetic field is studied for two parameterizations of nuclear density for wide set of nucleus-nucleus collisions at RHIC and the LHC energies ($\sqrt{s_{NN}}$), namely, for $Cu + Cu$ at $\sqrt{s_{NN}} = 22.6, 62.4$ and 200 GeV, $Cu + Au$ at $\sqrt{s_{NN}} = 200$ GeV, $Au + Au$ at $\sqrt{s_{NN}} = 7.7 - 200$ GeV, $Pb + Pb$ at $\sqrt{s_{NN}} = 2.76$ TeV and $U + U$ at $\sqrt{s_{NN}} = 193$ GeV. The preliminary eB dependence on proper time (τ) obtained for several collision types and $\sqrt{s_{NN}}$ is shown in figure 1 for central ($b/R = 0.7$), mid-central ($b/R = 1.15$) and peripheral ($b/R = 2.0$) interactions. At large τ as expected in accordance with [4] the eB increases significantly with the decrease of the collision energy in both the $Au + Au$ (figures 1a, b) and the $Cu + Cu$ (figures 1c, d) with opposite behaviour of peak eB values at very small τ. The eB shows the much more sharper decrease for $Pb + Pb$ collisions at the LHC energy for small τ (figure 1f) than that for highest RHIC energy $\sqrt{s_{NN}} = 200$ GeV. As seen the transition from the simplest case of the rigid sphere to the more realistic Fermi distribution for nuclear density leads to some decrease of the strength of magnetic field especially for RHIC energies.

3. Correlators of the charged particles

In the framework of CME model the theoretical correlator is given by [4, 5]

$$\langle \mathbf{K}^{\mathrm{T}}_{\alpha\beta} \rangle = \frac{\pi^2}{16} \frac{\langle \Delta_\alpha \Delta_\beta \rangle}{\langle N_\alpha N_\beta \rangle}, \quad \langle \Delta_\alpha \Delta_\beta \rangle = \kappa \alpha_S \left(\frac{\pi R}{2} \sum_f q_f^2 \right)^2 \varepsilon_{\alpha\beta} \int_{S_\perp} d^2 x_\perp \xi_{\alpha\beta}(x_\perp) \int_{\tau_i}^{\tau_f} d\tau \tau \left[eB(\eta, \tau) \right]^2 . \quad (2)$$

Here $\varepsilon_{\pm\pm} = -0.5\varepsilon_{\pm\mp} = 0.5$, $\xi_{\pm\pm}(x_\perp) \equiv \sum_{i=+,-} \xi_i^2(x_\perp, \lambda)$, $\xi_{\pm\mp}(x_\perp, \lambda) \equiv \prod_{i=+,-} \xi_i(x_\perp, \lambda)$, α_{S} – renormalized strong coupling constant, N_α – multiplicity of particles with electric charge sign α in event, q_f – electric charge (in units of e) of quark with flavor f, Δ_α is the difference between total charges with fixed sign α on each side of the reaction plane, numerical coefficient $\kappa \sim 1$, $x_\perp$ – position of nucleon from one of the colliding nuclei in the plane perpendicular to the beam axis, $S_\perp$ – area of overlap region of colliding nuclei in the transverse plane, functions $\xi_\pm(x_\perp, \lambda)$ take into account the suppression effect via screening length λ [3]. The correlators $\langle \Delta_\alpha \Delta_\beta \rangle$ are calculated for set of collision types and energies indicated above. The variation of the type of nucleus and $\sqrt{s_{NN}}$ allow the investigation of the energy and atomic number dependencies of $\langle \Delta_\alpha \Delta_\beta \rangle$ as well as the influence of both the parametrization of nuclear density and the λ on correlator values. The preliminary results are shown in figures 2 and 3.

The larger λ leads to noticeable increase of same-charge correlator $\langle \Delta_\pm^2 \rangle$ in $Cu+Cu$ collisions at some fixed $\sqrt{s_{NN}}$ (figure 2) as well as for heavy ion collisions ($Au + Au$). On the other hand

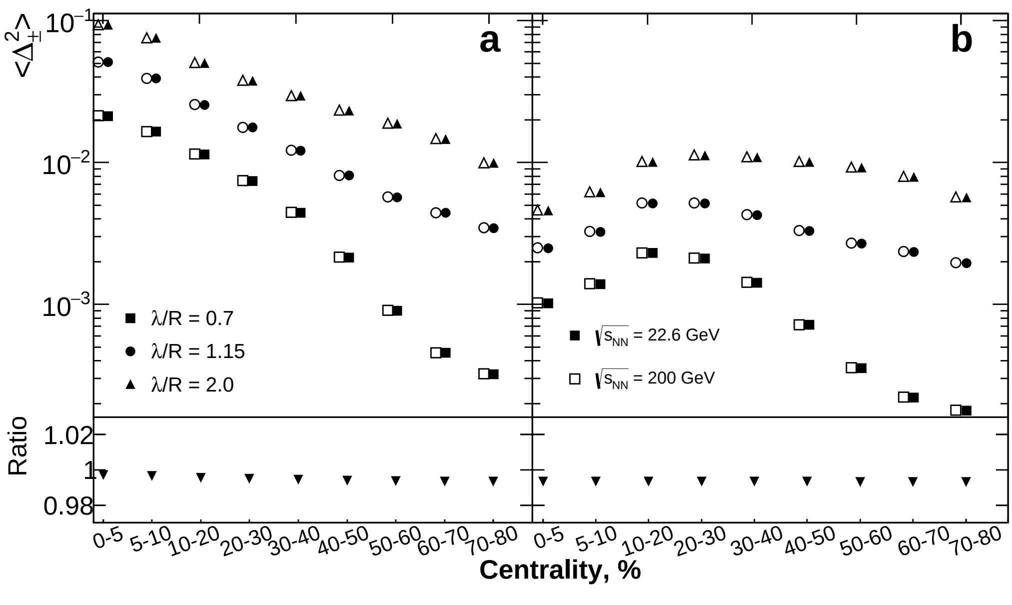

Figure 2. Centrality dependence of correlators for same-charged particle pairs in $Cu + Cu$ collisions for rigid sphere (a) and Fermi parametrization (b) for nuclear density at different λ/R and initial energies. The low panels show the ratio of correlator values at $\sqrt{s_{NN}} = 22.6$ GeV to the $\langle \Delta_\alpha \Delta_\beta \rangle$ at $\sqrt{s_{NN}} = 200$ GeV. Due to the structure of correlators this ratio is independent on λ.

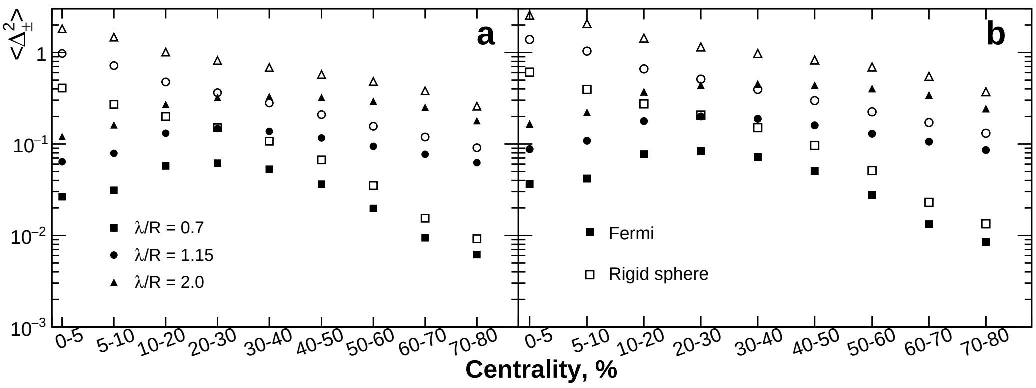

Figure 3. Centrality dependence of the correlator $\langle \Delta^2_\pm \rangle$ for $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV (a) and for $U + U$ at $\sqrt{s_{NN}} = 193$ GeV (b) for various screening lengths and parameterizations for nuclear density.

as seen in figure 2 the values of $\langle \Delta^2_\pm \rangle$ weakly depend on collision energy for wide range of $\sqrt{s_{NN}} = 22.6 - 200$ GeV. Furthermore the dependence of $\langle \Delta^2_\pm \rangle$ on $\sqrt{s_{NN}}$ in $Cu+Cu$ collisions is similar to that for interactions of heavy ions ($Au + Au$). It should be noted that the growth of multiplicity of secondary particles with increase of $\sqrt{s_{NN}}$ leads to the some decrease of the magnitudes of $\langle \mathbf{K}^{\mathrm{T}}_{\alpha\beta} \rangle$ as well as of corresponding experimental observables for higher energy nucleus-nucleus collisions. Therefore the energy dependence of $\langle \Delta^2_\pm \rangle$ obtained here agrees with expectations from [3, 4, 5]. In general the correlator values for same-charged particle pairs are smaller for Fermi parametrization than that for approach of rigid sphere at corresponding centralities. But the type of parametrization for nuclear density influences on the $\langle \Delta^2_\pm \rangle$ mostly for central collisions and this influence decreases for more peripheral collisions (figures 2, 3). The same-charge correlator values change weakly with increasing of atomic number in $Pb + Pb$ and $U + U$ interactions but the $\langle \Delta^2_\pm \rangle$ shows the noticeable increase at transition from moderate ($Cu + Cu$) to heavy ($Au + Au$, $Pb + Pb$, $U + U$) nucleus-nucleus collisions.

4. Conclusion

The strength of magnetic field in $A + A$ collisions as well as multiplicity-independent correlators within the framework of the CME are calculated for two parameterizations of nuclear density, namely, for rigid sphere and for two-component Fermi model. The calculations are made for wide set of beam types and collision energies. The more realistic Fermi distribution leads to some decrease of the strength of magnetic field especially for RHIC energies. For the first time the estimations of the magnetic field are calculated in asymmetric $Cu + Au$ collisions. The same-charge correlator magnitudes depend on collision energy weakly for $Cu + Cu$ and $Au + Au$, but this correlator increases noticeably with growth of atomic number from moderate to heavy nuclei. Comparison of correlator values with experimental observables is in the progress.

Acknowledgments

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