Charge-dependent azimuthal correlations from AuAu to UU collisions

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We study the charge-dependent azimuthal correlations in relativistic heavy ion collisions, as motivated by the search for the Chiral Magnetic Effect (CME) and the investigation of related background contributions. In particular we aim to understand how these correlations induced by various proposed effects evolve from collisions with AuAu system to that with UU system. To do so, we quantify the generation of magnetic field in UU collisions at RHIC energy and its azimuthal correlation to the matter geometry using event-by-event simulations. Taking the experimental data for charge-dependent azimuthal correlations from AuAu collisions and extrapolating to UU with reasonable assumptions, we examine the resulting correlations to be expected in UU collisions and compare them with recent STAR measurements. Based on such analysis we discuss the viability for explaining the data with a combination of the CME-like and flow-induced contributions.

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I. INTRODUCTION

The relativistic heavy ion collisions provide the unique way to create a new state of hot deconfined QCD matter known as the quark-gluon plasma (QGP). To measure and understand the properties of this QGP and its transition to the ordinary confined hadronic matter, being part of the early cosmos evolution history, is of fundamental interest. Such experiments are now carried out with a variety of collisional beam energies at the Relativistic Heavy Ion Collider (RHIC) as well as the Large Hadron Collider (LHC) [1–3]. Among many other observables, two-(and multi-)particle azimuthal correlations (i.e. how particles emitted along one direction on the transverse plane get related with particles emitted along another direction) play key roles. For example, practically all collective flow measurements are done through such correlations [4]. Other examples include, e.g., hard-soft di-hadron correlations which, via contrast between dA and AA, were instrumental in establishing the jet quenching phenomenon [2].

In the past several years, there have been significant interests in measuring and understanding the charge-dependent azimuthal correlations, that is, to study the azimuthal correlations separately for same-sign pairs (with ++ or − charges) and for opposite-sign pairs (with one + and the other −) - and to see their differences. A major motivation came from proposals in search of possible anomalous effects, such as the Chiral Magnetic Effect (CME) [5–9], Chiral Separation Effect (CSE) [10–12], Chiral Magnetic Wave (CMW) [13–19], Chiral Electric Separation Effect (CESE) [20], etc. Such effects arise from nontrivial interplay between chiral fermions and QCD topological objects that are abundant in hot QGP [21], and can be manifested as generation of vector and/or axial currents in response to external strong (electro)magnetic (EM) fields. The heavy ions (such as Au, U, or Pb nuclei) with large positive electric charges and moving at nearly speed of light, naturally provide the extremely strong EM fields (on the order of hadronic scales eE, eB ∼ mπ2) at the early moments in relativistic heavy ion collisions [5, 22–31]. A lot of works have been done in the past few years to hunt for these effects, especially the CME, by measuring the charge-dependent azimuthal correlations and analyzing their implications [32–37]. The precise interpretations of data and the contributions of various related background effects are still under intensive investigations [38–43], as recently reviewed in Ref. [44].

In this paper we focus on the CME motivated measurements, for which the following charge-charge azimuthal correlations were proposed [32] and measured both at RHIC [33–35] and at LHC [36, 37],

\[ \gamma_{\alpha\beta} = \langle \cos(\phi_i + \phi_j - 2\psi_{RP}) \rangle_{\alpha\beta} \]  

with \( \alpha, \beta = \pm \) and \( \phi_i \) and \( \phi_j \) being the azimuthal angles of two final state charged hadrons. The average \( \langle \cdot \cdot \cdot \rangle_{\alpha\beta} \) means first averaging over all pairs \( (\phi_i, \phi_j) \) that consist of one \( \alpha \) charged and one \( \beta \) charged hadrons and then averaging over all the events. Such azimuthal correlations are reaction-plane dependent and essentially measure the in-plane/out-of-plane difference of same-sign(SS) or opposite-sign(OS) pair correlations. The CME predicts a vector current and a resulting final hadron charge separation along the external magnetic field direction which is approximately out-of-plane. Therefore if CME is the only source contributing to these correlations, one expects the same-charge correlation \( \gamma_{\alpha\alpha} \) to be negative and the opposite-charge correlation \( \gamma_{\alpha\beta} \) to be positive, with the two having the same magnitude. The STAR data for \( \gamma_{SS} \) and \( \gamma_{OS} \) indeed shows the signs and centrality trends in accord with CME expectation. However in the complex environment of heavy ion collisions, there are other sources that could also contribute to these measured correlations. As first analyzed in [40], the existence of those “background effects” is best shown by another type of (reaction-plane independent) azimuthal correlations which were also measured:

\[ \delta_{\alpha\beta} = \langle \cos(\phi_i - \phi_j) \rangle_{\alpha\beta}. \]  

While the CME-induced same-charge pair correlation (in co-
moving pattern) would contribute positively to the above observable, the data show strongly negative $\delta_{SS}$ which means the dominant same-sign pair correlation would be in back-to-back pattern. These measurements together strongly suggest that there are non-CME “background” contributions, some of which have been identified recently, including e.g. the transverse momentum conservation (TMC) and the local charge conservation (LCC). In peripheral collision, the transverse momentum conservation (TMC) [39, 41] tends to give both same-charge and opposite-charge correlations a negative shift which is proportional to the elliptic flow $v_2$ and inversely proportional to multiplicity. The local charge conservation (LCC) [38] is another source: if the charges are forced to be neutralized over small domains in the fireball at freeze-out, then the collective flow will translate such spatial correlation into final (co-moving) moment correlation for opposite-charge pairs. Furthermore the elliptic flow will induce an in-plane/out-of-plane difference, thus giving a positive contribution to $\gamma_{\text{OS}}$ (while no contribution to $\gamma_{\text{SS}}$). This LCC-induced contribution originates from considering the fluid cells as canonical rather than grand-canonical ensemble of charges and such effect is also approximately inversely proportional to multiplicity.

In addition to the known (and potentially unknown) background effects, the CME-induced signals may also suffer from the strong initial state fluctuations of the matter geometry as well as the $\mathbf{B}$-field orientation. The event-by-event fluctuations generally make the $\mathbf{B}$ direction unaligned with the event-wise second-harmonic participant plane and hence tend to suppress the CME contributions to the $\gamma_{\alpha\beta}$ as thoroughly studied in [29]. For RHIC AuAu collisions it was found [29] that such suppression is extremely strong for very central and very peripheral collisions and the most promising centrality bins for detection of any $\mathbf{B}$-field induced effect is around $20 - 50\%$.

Clearly the present situation concerning the interpretations of the measured charge-dependent azimuthal correlations calls for a careful separation of the flow-driven background contributions. Note that both TMC and LCC effects’ contributions to $\gamma_{\alpha\beta}$ grows with the elliptic flow (i.e. increasing from central to peripheral collisions), however the $\mathbf{B}$ field strength also shows a similar centrality trend, thus making the separation rather difficult. There have been a few different proposals in attempt to achieve this [42, 44–46], one of which is to utilize the UU collisions [46]. The Uranium nucleus $^{238}\text{U}$, unlike the Au or Pb, has a highly deformed prolate shape with a large quadrupole. The initial idea is that for the very central UU collisions there will be negligible magnetic field but still sizable geometric anisotropy (e.g. due to the so-called “body-body” collision configuration) that leads to elliptic flow, so that any $\mathbf{B}$-related effect will be absent while any $v_2$-driven effect will still be present. Very recently, STAR collaboration reported their preliminary results of the charge-dependent azimuthal correlations in UU collisions at $\sqrt{s} = 193$ GeV [48]. The UU data show certain interesting features different from AuAu, and in particular for the most central events ($0 - 1\%$) they observe a sizable $v_2$ but vanishing $\gamma_{\text{OS}} - \gamma_{\text{SS}}$.

The meanings of these UU data, in connection with the AuAu data, require a careful examination of how various known sources of such correlations evolve from the AuAu system to the UU system. This is the main purpose of the present study. Our strategy will be to quantify the evolutions in the matter geometry (that drives flow) as well as in the EM fields from AuAu to UU, and then based on plausible assumptions to extrapolation different effects ($v_2$-related and $\mathbf{B}$-related) accordingly from AuAu to UU, and see if the correlations for both systems could be consistently understood as a combination of different effects. The rest of this paper is organized as follows. In Sec. II we will report the event-by-event calculation of the strength of the EM fields in UU collisions and the azimuthal correlations between $\mathbf{B}$-field orientation and the event-wise participant plane. In Sec. III we will then use these results to extrapolate the decomposed ($v_2$-related and $\mathbf{B}$-related) components of the correlations $\gamma_{\alpha\beta}$ from AuAu data to UU collisions and compare them with UU data. Finally we summarize in Sec. IV. The natural unit $\hbar = c = k_B = 1$ will be used throughout this paper.

## II. ELECTROMAGNETIC FIELDS IN UU COLLISIONS WITH INITIAL STATE FLUCTUATIONS

The possibility to study heavy ion collisions using UU system has been discussed for long, see e.g. [50–55]. Event-by-event simulations were also previously done to study the expectations for multiplicities as well as the geometric anisotropies in the initial conditions for UU collisions. However the strong electromagnetic fields, crucial for those field-induced effects in UU collisions, have not been quantified before. In this Section, we report our event-by-event determination of such EM fields and also importantly their azimuthal orientations with respect to the (concurrently fluctuating) initial matter geometry.

### A. Setup

We first discuss our setup for the event-by-event analysis of the electromagnetic fields generated in UU collision at $\sqrt{s} = 193$ GeV, following similar simulations done for AuAu collisions in [29]. Let us focus on the fields at the initial time, $t = 0$, that is, the time when the centers of the two colliding uranium nuclei both lie on the transverse plane. The time dependence of these fields will have no difference from that in AuAu case as previously studied (see e.g. [28, 30]). Throughout this Section we will show results for the field point at the center of fireball $x = y = z = 0$. EM fields at other transverse points have also been computed and compared with the AuAu case as in [29], and they all show the same trends. We utilize the following form of the Liénard-Wiechert potentials
for constantly moving charges:

\[ e\mathbf{E}(t, r) = \frac{e^2}{4\pi} \sum_n Z_n(r_n) \frac{1 - v_n^2}{[R_n^2 - (r_n \times v_n)^2]^{3/2}} r_n, \]  

\[ e\mathbf{B}(t, r) = \frac{e^2}{4\pi} \sum_n Z_n(r_n) \frac{1 - v_n^2}{[R_n^2 - (r_n \times v_n)^2]^{3/2}} v_n \times r_n, \]  

(2.1) (2.2)

where \( r_n = r - r_n(t) \) is the relative position of the field point \( r \) to the \( n \)th proton at time \( t \), \( r_n(t) \), and \( v_n \) is the velocity of the \( n \)th proton. The summations run over all protons in the projectile and target nuclei. Equations (2.1) and (2.2) contain singularities at \( R_n = 0 \) if we treat protons as point charges. In practical calculation, to avoid such singularities we treat protons as uniformly charged spheres with radius \( R_p \). The charge number factor \( Z_n(r_n) \) in Eqs. (2.1) and (2.2) is introduced to encode this aspect: when the field point locates outside the \( n \)th proton (in the rest frame of the proton) \( Z_n = 1 \), otherwise \( Z_n < 1 \) depends on \( r_n \). The in-medium charge radius \( R_p \) of proton is unknown, thus we use the vacuum value \( R_p = 0.84184(67) \text{ fm} \) [56] in our numerical simulation.

The nucleons in one nucleus move at constant velocity along the beam direction (we choose it as \( z \)-direction) while the nucleons in the other nucleus move at the same speed but opposite direction. The energy for each nucleon is set to be \( \sqrt{s}/2 \) in the center-of-mass frame, therefore the value of the velocity of each nucleon is given by \( v_n^2 = 1 - (2m_N/\sqrt{s})^2 \), where \( m_N \) is the mass of the nucleon. We set the \( x \)-axis along the impact parameter vector so that the reaction plane is the \( x-z \) plane. Finally, the positions of nucleons in the rest frame of a uranium nucleus are sampled according to a deformed Woods-Saxon distribution (in spherical coordinates) [53–55],

\[ \rho(r, \theta) = \frac{\rho_0}{1 + \exp((r - R'(\theta))/a)}, \]  

\[ R'(\theta) = R[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)], \]  

(2.3) (2.4)

where \( \rho_0 = 0.16 \text{ fm}^{-3} \) is the normal nuclear density, \( R \) and \( a \) denote the “radius” of the nucleus and the surface diffuseness parameter. The parameters \( \beta_2 \) and \( \beta_4 \) specify the shape deformation of the nucleus from sphere \( (\beta_2 = \beta_4 = 0) \). \( Y_n^m(\theta) \) denotes spherical harmonics and \( \theta \) is the polar angle with respect to the symmetry axis of the nucleus. The values of the parameters for \( {}^{238}\text{U} \) are \( R = 6.81 \text{ fm}, a = 0.55 \text{ fm}, \beta_2 = 0.28 \), and \( \beta_4 = 0.093 \). The positions of nucleons are sampled by \( 4\pi r^2 \sin \theta \rho(r) \theta d\theta d\phi \) with appropriate normalization. Different though from the AuAu collisions, in the UU case the polar and azimuthal directions of the rotation-symmetric axis for each of the colliding uranium nuclei are randomly (and independently) orientated on the event-by-event basis with probability density \( \sin \Theta \) and uniform distribution for \( \Theta \) and \( \Phi \), respectively. Here, \( \Theta \) and \( \Phi \) are the solid angles of the rotation-symmetric axis of each nucleus. The \( \sin \Theta \) weight needs to be implemented to simulate unpolarized nucleus-nucleus collisions. For each given impact parameter we sample 100 different orientational configurations.

In Fig. 1, we show the result for the event-averaged \( y \)-component of the magnetic field, \( \langle eB_y \rangle \), generated in UU collision at \( \sqrt{s} = 193 \text{ GeV} \). The negative values have no particular meaning, only related to choice of which nucleus is running which way from beam pipe view.) Despite the fact that the shape of uranium nucleus is rather different from sphere, after event average, its effects in generating electromagnetic fields are nearly equivalent to a spherical nucleus. Indeed, it is seen from Fig. 1 that the magnitude and the impact parameter dependence of \( \langle eB_y(b) \rangle \) in UU collisions are very close to that in AuAu collision at \( \sqrt{s} = 200 \text{ GeV} \) (as reported in e.g. [27, 28]). Other components, \( \langle eB_x, z \rangle \), of the magnetic field and the electric field \( \langle eE \rangle \) are essentially zero after event average.

As already shown in the AuAu and PbPb cases [29], the event-by-event position fluctuation of the protons in the colliding nuclei can bring interesting features, for example, a large field strength square, even for central collision. The similar situation happens for UU collision, see Fig. 2 for the event-averaged magnetic field square and electric field square, \( \langle (eB)^2 \rangle \) and \( \langle (eE)^2 \rangle \). We see that on the event-by-event basis, the magnitudes of \( \langle (eB)^2 \rangle \) and \( \langle (eE)^2 \rangle \) are smaller than that in AuAu collisions reported in [29]: the nucleus shape matters in this sense.
For the convenience of comparison with experimental data later, we also plot \( \langle eB_y \rangle \) and \( \langle (eB)^2 \rangle \) as functions of the charged particle multiplicity per unit pseudorapidity (we will simply call it multiplicity) near mid-rapidity region. We adopt the following two component model [57]

\[
\frac{dN_{ch}}{d\eta} = n_{pp} \left[ (1 - x) \frac{N_{\text{part}}}{2} + x N_{\text{coll}} \right]
\]

to describe the multiplicity as functions of participant number \( N_{\text{part}} \) and binary collision number \( N_{\text{coll}} \), where \( n_{pp} \approx 2.42 \) is the energy-dependent charge multiplicity of proton-proton collision at \( \sqrt{s} = 193 \text{ GeV} \) and \( x = 0.13 \) is the fraction of charged multiplicity generated in binary nucleon-nucleon collisions [49]. The multiplicity dependence of \( \langle eB_y \rangle \) and \( \langle (eB)^2 \rangle \) are shown in Fig. 3 and Fig. 4.

C. Azimuthal correlation between the B-field orientation and the participant planes

We now turn to study the azimuthal correlation between the magnetic field and the participant plane, i.e., we will calculate \( \langle \cos(2(\psi_B - \psi_2)) \rangle \) and \( \langle (eB)^2 \cos(2(\psi_B - \psi_2)) \rangle / \langle (eB)^2 \rangle \) where \( \psi_B \) is the azimuthal angle of the magnetic field and \( \psi_2 \) is the azimuthal angle of the second harmonic participant plane. The motivation and importance of such a study has been explained in [29]: basically the B-field-induced effect will bear such a suppression factor, so the quantitative contribution of such an effect is controlled not by \( \langle (eB)^2 \rangle \) but by \( \langle (eB)^2 \cos(2(\psi_B - \psi_2)) \rangle \) which may be called the “projected field strength”. Let us mention in passing that the matter geometry itself is fluctuating, and with our event-by-event simulations we determine the harmonic participant planes for each event as usually done in the literature (see e.g. [29]).

In Fig. 5 and Fig. 6 we show these azimuthal correlations in UU collision as functions of impact parameter and the multiplicity, respectively. Again, we see that the correlations (as functions of \( b \)) behave similarly as that in AuAu collision: at small and large impact parameters the correlations are strongly suppressed while the strongest correlations (~ 0.7) occur around \( b \approx 10 \text{ fm} \) or \( dN_{ch}/d\eta \) around 200.

It is of great interest to compare the important quantity \( \langle (eB)^2 \cos(2(\psi_B - \psi_2)) \rangle \) that controls the strength of B-induced effect for both UU and AuAu collisions: see Fig. 7. We see that this strength in UU collision is generally weaker than that in AuAu collision for most of the centrality except for the very central and very peripheral cases when both tend to vanish.

We have also studied the azimuthal correlations between B-
we show the very similar patterns as in AuAu collisions [39], including the impact parameter dependence of \( n = 1, 3 \) cases.

III. IMPLICATIONS ON THE CHARGE-DEPENDENT AZIMUTHAL CORRELATIONS

In this Section we conduct an extrapolation study from AuAu to UU systems. With the event-by-event simulations done for UU above and for AuAu previously in [29], we know how the matter geometry (i.e. eccentricity \( e_2 \) driving elliptic flow) changes from AuAu to UU, and we know how the \( B \) field and its orientation (which drives effect like CME) changes from AuAu to UU. So with reasonable assumptions one may develop extrapolations on how the contributions to charge-dependent correlations from the two types of sources, the \( v_2 \)-related and the \( B \)-related, would evolve from AuAu to UU systems. In what follows, we will first try to decompose the two types of sources in the AuAu data, and then extrapolate them respectively to UU, and see if a reasonable description of UU data would be achieved by such a combination of different effects.

A. Decomposition of the charge-dependent azimuthal correlations

Let us focus on the CME-motivated azimuthal correlation (which itself is parity-even, able to measure the fluctuations of a parity-odd charge dipole)

\[
\gamma_{\alpha\beta} = \langle \cos(\phi_i + \phi_j - 2\psi_{RP}) \rangle_{\alpha\beta}. \tag{3.1}
\]

It is also important to simultaneously examine the other charge-dependent azimuthal correlation

\[
\delta_{\alpha\beta} = \langle \cos(\phi_i - \phi_j) \rangle_{\alpha\beta}. \tag{3.2}
\]

To simplify the notation, we will also use \( \gamma_{SS} \) (SS for same sign) and \( \gamma_{OS} \) (OS for opposite sign) to denote \( \gamma_{++/--} \) and \( \gamma_{+/-+,--} \) (similarly for \( H_{SS,OS}, F_{SS,OS}, \delta_{SS,OS} \) below), respectively.

The CME-induced correlations, as well understood before (see e.g. discussions in [40, 44]), would make the following contributions to these correlations:

\[
\gamma_{CME}^{\alpha\beta} \equiv -H_{\alpha\beta} , \delta_{CME}^{\alpha\beta} = H_{\alpha\beta}. \tag{3.3}
\]

with \( H_{SS} \simeq -H_{OS} > 0 \).

As already discussed in the Introduction, there are other-than-CME “background” contributions to both \( \gamma \) and \( \delta \), including the transverse momentum conservation (TMC) or the local charge conservation (LCC). The dynamical mechanisms of both effects are intrinsically reaction-plane independent, with TMC inducing a charge-independent back-to-back correlation while the LCC inducing a near-side (co-moving) correlation solely in the same sign pair correlation. They however make a flow-dependent contribution to the reaction-plane dependent correlation \( \gamma \) due to the anisotropy in the particle azimuthal distribution as quantified by \( v_2 \). As briefly analyzed in [44], the contributions of these effects to the \( \delta \) and the \( \gamma \) are related by a factor of \( v_2 \).

One can therefore make the following plausible decomposition of the two types, CME-like and \( v_2 \)-related, contributions to these correlations in the following two-component way:

\[
\gamma_{\alpha\beta} = v_2 F_{\alpha\beta} - H_{\alpha\beta}, \tag{3.4}
\]

\[
\delta_{\alpha\beta} = F_{\alpha\beta} + H_{\alpha\beta}. \tag{3.5}
\]

where \( F_{\alpha\beta} \) are the \( v_2 \)-related background contributions and \( H_{\alpha\beta} \) are the CME contributions. With such working assumptions, we can then use the STAR AuAu collision data for...
\[ \gamma_{\alpha\beta}, \delta_{\alpha\beta} [33, 34, 48], \text{and } v_2 \text{ to extract } F_{\alpha\beta} \text{ and } H_{\alpha\beta} \text{ as functions of centrality or multiplicity. The result of such a decomposition is shown in Fig. 9. In the decomposition, we have used } v_2(\eta \text{ sub}) [47]; \text{ using other measurements of } v_2, \text{ like } v_2(\{\text{EP}\}), v_2(\{2\}) \text{ gives minor difference in } h \text{ and } f \text{ below. From the plots one can see that: 1) the flow-related parts, } F_{OS,SS} \text{ (including their centrality trends) can be reasonably understood as a combination of TMC and LCC, with TMC making the negative contributions to both the } F_{SS} \text{ and } F_{OS} \text{ while the LCC making a strong positive contribution to the opposite sign correlations accounting for the difference between } F_{SS} \text{ and } F_{OS}; \text{ 2) the remaining correlations (that are unrelated to } v_2 \text{ in the } H \text{ still show charge-dependence and the } H_{SS} \text{ appears in line with the CME expectation; 3) the } H_{OS} \text{ for most centrality is positive (which is different from CME expectation), and a plausible explanation of } H_{OS,SS} \text{ together could be that a charge-independent effect (such as the matter dipole fluctuations pointed out in [58]) contributes to both while the CME accounts for the difference between } H_{OS} \text{ and } H_{SS}. \text{ Lastly, it is worth emphasizing that a single component assumption with only flow-related contributions would not work for describing all the data and a CME-like component appears necessary for a full description of full data set.}

A useful way to eliminate any charge-independent contributions and focus on the truly charge-dependent contributions is to make a subtraction between SS and OS signals,

\[ \Delta \gamma \equiv \gamma_{OS} - \gamma_{SS}, \]
\[ \Delta \delta \equiv \delta_{OS} - \delta_{SS}. \]

In \( \Delta \gamma \) and \( \Delta \delta \), charge independent sources are then subtracted out. Now, from Eqs. (3.4)-(3.5), we can write

\[ \Delta \gamma = f v_2 - h(\langle eB \rangle^2 \cos[2(\psi_B - \psi_2)]), \]
\[ \Delta \delta = f + h(\langle eB \rangle^2 \cos[2(\psi_B - \psi_2)]), \]

In the above, \( f = F_{OS} - F_{SS} \) while the \( h(\langle eB \rangle^2 \cos[2(\psi_B - \psi_2)]) = H_{OS} - H_{SS} \) where we have assumed that the CME-like signal in \( H_{OS} - H_{SS} \) is B-field driven and explicitly singled out the dependence on the “projected field strength”. Finally we assume that the two functions \( f \) and \( g \) introduced in Eqs.(3.8)(3.9) are dominantly determined by multiplicity \( dN_{ch}/d\eta \), i.e. \( f = f(dN_{ch}/d\eta) \) and \( h = h(dN_{ch}/d\eta) \) for a given collisional beam energy (noting that the AuAu 200 GeV and UU 193 GeV could be considered approximately the same for all practical purposes). This assumption is plausible as we have explicitly separated the other important factors \( v_2 \) and \( \langle (eB)^2 \cos[2(\psi_B - \psi_2)] \rangle \) in such correlations. One can then extract these two functions from the \( F_{\alpha\beta} \) and \( H_{\alpha\beta} \) in Fig. 9 and the information about the “projected field strength” (from [29]): the results of \( f \) and \( h \) are shown...
in Fig. 10. Theoretically both functions may be expected to have a crude linear dependence on inverse multiplicity, and we have attempted to test this by fitting analysis, with these fitting curves also shown in Fig. 10. It is found that \( f(x) \propto 1/x \) at high multiplicity region and \( 1/x^{0.6} \) at low multiplicity region; while \( h(x) \propto 1/x \) at low multiplicity region and \( h \) is roughly a constant when multiplicity is large i.e. the \( h \) appears to be saturated at very high multiplicity.

B. Extrapolation from AuAu to UU collisions and comparison with STAR data

We are now ready to make an extrapolation analysis from AuAu to UU collisions. Our starting point is to assume that the two decomposition relations in Eq. (3.8) and Eq. (3.9) apply to UU collisions as well, with three important ingredients from the two types of sources in AuAu collisions (as measured by STAR [48]): 1) the projected field strength \( (\langle \epsilon B \rangle^2 \cos[2(\psi_{18} - \psi_2)]) \) to be used are the values for AuAu system (as shown in Fig. 7); 2) the \( v_2 \) to be used are the measured values in UU collisions at given multiplicity (as measured by STAR [48]); 3) the two functions \( f[\langle N_{ch}/d\eta \rangle] \) and \( h[\langle N_{ch}/d\eta \rangle] \) are assumed to stay the same as extracted from AuAu analysis and shown in Fig. 10 (with slight numerical extrapolation to somewhat larger multiplicity). With these we are then able to make a reasonable “guess” of the azimuthal correlations \( \Delta \gamma \) and \( \Delta \delta \) in UU collisions that could be confronted with measured data.

In Fig. 11 we show our results from extrapolation analysis for \( \Delta \gamma \) and \( \Delta \delta \) in UU collisions at \( \sqrt{s} = 193 \) GeV, with STAR preliminary data for \( \Delta \gamma \) [48] also shown. As one can see, the extrapolated results are fairly close to (but not exactly as) the data except for the very low multiplicity region. To have a more detailed understanding of the contributions from the two types of sources in the correlations, we show in Fig. 12 the respective contributions from CME-like source and \( v_2 \)-related source to \( \Delta \gamma \). Interestingly we find that each individual source could give a fairly reasonable account of the data but the added total is exceeding the data considerably. It might appear tempting to simply resort to an explanation that one of the two sources would be gone somehow in AuAu system. We however feel that might be somewhat naive, especially provided that the two components are clearly both needed for AuAu data and that after all there should be no drastic difference between AuAu and UU collisions after differences in factors like geometry, \( B \) field and multiplicity have all been explicitly accounted for.

Finally in Fig. 13 we plot the azimuthal correlations \( \Delta \gamma \) (scaled up by \( N_{part} \) following convention in [48]) versus \( v_2 \) for both AuAu and UU collisions, in comparison with available data [48]. While the general trends and order of magnitude for extrapolation results and the preliminary data are in crude proximity, a quantitative agreement is not in place. Nevertheless, an interesting observation is that our UU curve from extrapolation is nearly parallel to the data curve: if one multiplies our curve by a factor of 0.7 then the shifted curve would be in excellent agreement with data: the origin of such a simple-factor discrepancy is not clear at the moment. So what can one learn from the mismatch between the extrapolated results and the data for AuAu system? Logically there could be varied reasons: 1) it could be due to the assumption that the functions \( f \) and \( g \) in Fig. 10 could be simply extrapolated from AuAu to UU; 2) it could be that the way of linearly combining the two types of identified sources may not be entirely true and there could be other unknown type of sources contributing to the correlations. It however should be emphasized that there is no indication of non-existence for any of the two types of already identified (\( v_2 \)-related and CME-like) sources.

Last but not least, let us emphasize also certain ambiguities on the data aspects. In particular there appears to be noticeable difference between the two elliptic flow \( v_2 \) data sets for AuAu: one reported in [47] (which was used by us in the decomposition analysis via Eqs.(3.8)(3.9)), and the other shown in [48] which compared AuAu and UU \( v_2 \). Such differences may bear significant impact on our extrapolation analysis. A finalized UU data set with more detailed systematics information on multiplicity, flow, \( \gamma_{\alpha\beta} \) as well as \( \delta_{\alpha\beta} \) from the experimental side would be highly desirable for further analysis.

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**Fig. 11:** (Color online) The extrapolation results for charge-dependent azimuthal correlations \( \Delta \gamma \) and \( \Delta \delta \) in UU collisions at \( \sqrt{s} = 193 \) GeV (see text for details). The open circles are STAR preliminary data [48].

**Fig. 12:** (Color online) Contributions from different sources to the correlation \( \Delta \gamma \) for UU collisions at \( \sqrt{s} = 193 \) GeV (see text for details). The open circles are STAR preliminary data [48].
are from our analysis and the open symbols are STAR preliminary

to clarify the situation. One may also notice that there is a
“turning” behavior on the upper right end of the curve: this
corresponds to the region of small multiplicity or peripheral
collisions where the \( v_2 \) has non-monotonic dependence (arising
from a competition between increasing initial eccentric-
ity and decreasing density thus smaller pressure gradient that
pushes flow) on multiplicity (see e.g. data plot in [48]).

IV. SUMMARY AND DISCUSSIONS

In summary, we have studied the charge-dependent az-
imuthal correlations in relativistic heavy ion collisions, as mo-
tivated by the search for the Chiral Magnetic Effect (CME)
and the investigation of related background contributions. In
particular we have attempted to understand how these corre-
lations induced by various proposed effects evolve from colli-
sions with AuAu system to that with UU system.

To do that, we have first systematically studied the elec-
tromagnetic fields generated in the RHIC UU collisions at
\( \sqrt{s} = 193 \text{ GeV} \), incorporating initial state fluctuations on
events-by-event basis. The fluctuations of the proton position
in nucleus cause the fluctuations in the electromagnetic
fields, on which one hand cause sizable electromagnetic field
even for some very central events while on the other hand
suppress the correlation between the B-field orientation and
the matter geometry (characterized by event-wise participant
plane). We have quantified the “projected field strength”
\( \langle (eB)^2 \cos[2(\psi_B - \psi_2)] \rangle \) (in Fig. 7) which control the B-field
induced effects such as the CME. We have then used these results to study the recent charge-
dependent azimuthal correlation measurements by STAR col-
laboration for UU collisions at \( \sqrt{s} = 193 \text{ GeV} \). Taking the ex-
perimental data for charge-dependent azimuthal correlations
from AuAu collisions, we have developed a two-component
decomposition (see Eq. (3.4) and Eq. (3.5)) based on two
types of identified sources (\( v_2 \)-related and CME like) that
could contribute to the measured correlations. We have fur-
ther extrapolated each component to UU system with rea-
sonable assumptions and compared the resulting correlations
with data from UU collisions. and compare them with re-
cent STAR measurements. Based on such analysis we discuss
the viability for explaining the data with a combination of the
CME-induced and flow-induced contributions. The extrap-
olation results have demonstrated similar trend and order-of-
magnitude agreement with data while still bearing quantitative
discrepancy. From these studies it may be concluded that the
suggested two-component scenario with \( v_2 \)-related and CME-
like contributions may be a viable explanation of the mea-
sured charge-dependent azimuthal correlations, but also calls
for more careful modelings and more detailed experimental
information.

We end with a brief discussion on the evolution of these cor-
relations \( \gamma \) and \( \delta \) with collisional beam energies in light of the
two-component scenario. In general one would expect vari-
ations of the functions \( f \) and \( h \) with beam energy, and that is
why an extrapolation analysis to other beam energies becomes
difficult. For example, going to low energy collisions (as done
in RHIC Beam Energy Scan), the physics could change dras-
tically with the “turning-off” of a dominant piece of QGP in
the fireball evolution. At low enough energy one may expect
the disappearance of CME (when the medium is no longer
chirally restored) as well as the disappearance of the LCC
(when the charge-carriers are not mobile enough to ensure lo-
cal charge neutrality) — in that case the \( \Delta \gamma \) would approach
zero as indeed seen in data [48]. Going to the higher energy
collisions as at LHC, one might expect a qualitatively similar
pattern of the multiplicity-dependence of \( f \) and \( h \) as shown in
Fig.10, though possibly with overall magnitude shifting
mildly. For the CME-like component, its energy dependence
critically depends on the magnetic field: both its magnitude
and its duration in time. While the magnitude scales approxi-
amately as \( \sqrt{s}/M \) (with \( M \) the proton mass) and time dura-
tion scales in the inverse way as \( 1/(\sqrt{s}/M) \) so the energy
dependence of B field may turn out to be rather mild. Going
from RHIC to LHC energies, the integrated flow \( v_2 \) does not
change much but the multiplicity at LHC (for same centrality
class) does increase a lot (by about a factor \( \sim 2 \)). Noting that
the function \( h \) (for CME-like source) tends to be saturated for
increasing multiplicity while the function \( f \) (for flow-related
source) tends to be suppressed toward increasing multiplic-
ty, one would then expect that the \( \Delta \gamma \) at LHC would be
quite close to that at RHIC while the \( \Delta \delta \) would be somewhat
smaller at LHC than at RHIC: both seem to be in line with the
ALICE data [36].

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