Scaling properties of background- and chiral-magnetically-driven charge separation: implications for the chiral magnetic effect in heavy ion collisions

Roy Lacey

1Depts. of Chemistry & Physics, Stony Brook University, Stony Brook, New York 11794, USA

Abstract. The scaling properties of the $R_{\Psi^2}(\Delta S)$ correlator and the $\Delta \gamma$ correlator are used to investigate a possible chiral-magnetically-driven (CME) charge separation in $p+Au$, $d+Au$, Ru+Ru, Zr+Zr, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, and in $p+Pb$ ($\sqrt{s_{NN}} = 5.02$ TeV) and Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV. The results for $p+Au$, $d+Au$, $p+Pb$, and Pb+Pb collisions, show the $1/N_{ch}$ scaling for background-driven charge separation. However, the results for Au+Au, Ru+Ru, and Zr+Zr collisions show scaling violations which indicate a CME contribution in the presence of a large background. In mid-central collisions, the CME accounts for approximately 27% of the signal + background in Au+Au and roughly a factor of two smaller for Ru+Ru and Zr+Zr, which show similar magnitudes.

Metastable domains of gluon fields with non-trivial topological configurations can form in the magnetized chiral relativistic quark-gluon plasma (QGP) [1] produced in collisions at RHIC and the LHC. The colliding ions generate the magnetic field ($\vec{B}$) at early times [2]. The interaction of chiral quarks with the gluon fields can drive a chiral imbalance resulting in an electric current $\vec{J}_V = \frac{N_c e B}{2 \pi^2} \mu_A$, along the $\vec{B}$-field, i.e., perpendicular to the reaction plane; $N_c$ is the color factor, and $\mu_A$ is the axial chemical potential that quantifies the imbalance between right- and left-handed quarks. The resulting final-state charge separation, termed the chiral magnetic effect (CME) [1], is of great experimental and theoretical interest. However, its experimental characterization has been hampered by significant background.

The charge separation can be quantified via the $P$-odd sine term $a_1$, in the Fourier decomposition of the charged-particle azimuthal distribution [3]:

$$\frac{dN_{ch}}{d\phi} \propto 1 + 2 \sum_n (v_n \cos(n\Delta \phi) + a_n \sin(n\Delta \phi) + ...)$$

(1)

where $\Delta \phi = \phi - \Psi_{RP}$ gives the particle azimuthal angle with respect to the reaction plane (RP) angle, and $v_n$ and $a_n$ denote the coefficients of the $P$-even and $P$-odd Fourier terms, respectively. A direct measurement of $a_1$, is not possible due to the strict global $P$ and $CP$ symmetry of QCD. However, their fluctuation and/or variance $\tilde{a}_1 = \langle a_1^2 \rangle^{1/2}$ can be measured with charge-sensitive correlators such as the $\gamma$-correlator [3] and the $R_{\Psi^2}(\Delta S)$ correlator [4].

The $\gamma$-correlator measures charge separation as: $\gamma_{\alpha \beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$, $\Delta \gamma = \gamma_{OS} - \gamma_{SS}$, where $\Psi_2$ is the azimuthal angle of the 2nd-order event plane which fluctuates

*e-mail: Roy.Lacey@Stonybrook.edu

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about the RP, \( \phi \) denote the particle azimuthal emission angles, \( \alpha, \beta \) denote the electric charge (\(+\) or \(-\)) and SS and OS represent same-sign (\(++\), \(--\)) and opposite-sign (\(+-\)) charges. Measurements of the quotient \( \Delta \gamma/v_2 \) with the 2nd-order anisotropy coefficient \( v_2 \), are usually employed to aid quantification of the background-driven charge separation.

The \( R_{\Psi_2}(\Delta S) \) correlator measures charge separation relative to \( \Psi_2 \) via the ratio:

\[
R_{\Psi_2}(\Delta S) = \frac{C_{\Psi_2}(\Delta S)}{C_{\Psi_2}^g(\Delta S)},
\]

where \( C_{\Psi_2}(\Delta S) \) and \( C_{\Psi_2}^g(\Delta S) \) are correlation functions that quantify charge separation \( \Delta S \), approximately parallel and perpendicular (respectively) to the \( \vec{B} \)-field. The charge-shuffling procedure used to construct the correlation functions ensures identical properties for their numerator and denominator, except for the charge-dependent correlations, which are of interest [4]. \( C_{\Psi_2}(\Delta S) \) measures both CME- and background-driven charge separation while \( C_{\Psi_2}^g(\Delta S) \) measures only the background. After correcting the \( R_{\Psi_2}(\Delta S) \) distributions for the effects of particle-number fluctuations and the event-plane resolution, their inverse variance \( \sigma_{R_{\Psi_2}}^{-2} \) are used to quantify the charge separation [4].

In this work, we use model simulations to chart the scaling properties of \( \sigma_{R_{\Psi_2}}^{-2} \) and \( \Delta \gamma/v_2 \) for the background and signal + background, respectively, in A+A collisions. We then leverage these scaling properties to identify and characterize a possible CME-driven charge separation using previously published data for \( p+Au \), \( d+Au \), \( Ru+Ru \), \( Zr+Zr \) and \( Au+Au \) collisions at RHIC [5–10], and \( p+Pb \) and \( Pb+Pb \) collisions at the LHC [11–14].

Figure 1 shows the results for \( \sigma_{R_{\Psi_2}}^{-2} \) and \( \Delta \gamma/v_2 \) obtained with the AVFD and Hijing models for Au+Au collisions. Note that these models emphasize different sources for the charge-dependent non-flow background; the initial axial charge density \( n_5/s \) and the degree of local charge conservation (LCC) regulate the magnitude of the CME- and background-driven charge separation in the AVFD model. The solid triangles in Fig. 1 show that the background scales as \( 1/N_{ch} \) – the expected trend for the charge-dependent non-flow correlations. By contrast, the signal (Sig.) + background values (solid diamonds) indicate positive deviations from the background scaling [16, 17]. This dependence can be represented as:

\[
\Delta \gamma/v_2 = a + b/(N_{ch})^{-c}, \quad \text{and} \quad \sigma_{R_{\Psi_2}}^{-2} = a' + b'/(N_{ch})^{-c'},
\]

for the small values of \( n_5/s \) indicated in Fig. 1. Here, \( a, b \) and \( c \) are parameters; \( c \) characterizes the degree of the scaling violation.
Note that for \( c \approx 0 \) the \( 1/N_{\text{ch}} \) scaling for the background is retrieved, as demonstrated with the AVFD model in Fig. 1.

The scaling violation gives a direct signature of the CME-driven contributions to the charge separation (Figs. 1 (a) and (c)). It can be quantified via the fraction: 
\[
\frac{\Delta \gamma/v_2}{\Delta \gamma/v_2} = \frac{[\Delta \gamma/v_2(S \text{ig.} + Bkg.) - \Delta \gamma/v_2(Bkg.)]/[\Delta \gamma/v_2(S \text{ig.} + Bkg.)]}{[\sigma^{-2}_{R_{v_2}}(S \text{ig.} + Bkg.) - \sigma^{-2}_{R_{v_2}}(Bkg.)]/[\sigma^{-2}_{R_{v_2}}(S \text{ig.} + Bkg.)]}.
\]

The scaling patterns in Fig. 1 suggest that the observation of \( 1/N_{\text{ch}} \) scaling for the experimental \( \sigma^{-2}_{R_{v_2}} \) and \( \Delta \gamma/v_2 \) measurements would strongly indicate background-driven charge separation with little room for a CME contribution. However, observing a violation of this \( 1/N_{\text{ch}} \) scaling would indicate the CME-driven contribution. Figs. 1 (a) and (c) also indicate comparable background and signal + background \( \sigma^{-2}_{R_{v_2}} \) and \( \Delta \gamma/v_2 \) values in central and peripheral collisions, suggesting that the background dominates over that of the CME-driven contributions in these collisions. Note the reduction of \( \bar{B} \) in central collisions and the enhanced de-correlation between the event plane and the \( \bar{B} \)-field in peripheral collisions. Since the background dominates in central and peripheral collisions, the \( \sigma^{-2}_{R_{v_2}} \) and \( \Delta \gamma/v_2 \) measurements for these collisions can be leveraged with \( 1/N_{\text{ch}} \) scaling to obtain a quantitative estimate of the background over the entire centrality span (cf. Fig. 1). Here, an important proviso is to experimentally establish that the background in \( p(d)+A \) and \( A+A \) collisions scale over the full centrality span.

The \( v_2 \) and \( \Delta \gamma \) values reported for \( p+Au, d+Au, Ru+Ru, Zr+Zr \) and \( Au+Au \) collisions at RHIC [5–10], and \( p+Pb \) and \( Pb+Pb \) collisions at the LHC [12–15] were used to investigate the scaling properties of \( \Delta \gamma/v_2 \). Fig. 2 shows the results for \( p+Pb \) and \( Pb+Pb \) collisions at \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \). They indicate that \( \Delta \gamma/v_2 \) essentially scales as \( 1/N_{\text{ch}} \) \( (c \approx 0) \), suggesting negligible CME contributions in these collisions. They also confirm that the combined sources of background (LCC, resonances, back-to-back jets, ...), which should be substantial, especially for \( p+Pb \), scale as \( 1/N_{\text{ch}} \). Note as well that the CME contribution is negligible in \( p(d)+A \) collisions because of significant reductions in \( \bar{B} \), and the sizable de-correlation between the event plane and the \( \bar{B} \)-field [12]. Thus, the scaling patterns of \( \Delta \gamma/v_2 \) for these systems’ sizable backgrounds give a direct experimental constraint on the validity of \( 1/N_{\text{ch}} \) scaling of the background.
The scaling results for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 3. The $1/N_{ch}$ scaling apparent for $d+Au$ collisions (Fig. 3 (a)) confirms the expectation that the CME is negligible in these collisions. It also confirms that the combined sources of background (LCC, resonances, back-to-back jets, ...), which could be substantial in $d+Au$ collisions, show $1/N_{ch}$ scaling. In contrast to $d+Au$, the results for Au+Au (Fig. 3(b)) show visible indications of a violation ($c > 0$) to the $1/N_{ch}$ scaling observed for background-driven charge separation in $p(d)+A$ collisions. Similar violations were observed for Ru+Ru and Zr+Zr [17]. The scaling violation is similar to that observed for signal + background in Figs. 1 (a) and (c), suggesting an unambiguous non-negligible CME contribution to the measured $\Delta \gamma/v_2$ in Au+Au, Ru+Ru, and Zr+Zr collisions. The estimates of the background for all three systems are obtained by leveraging the $\Delta \gamma/v_2$ measurements for peripheral and central collisions with $1/N_{ch}$ scaling [17]. Here, it is noteworthy that the simulated results from the AVFD and HIJING models, as well as the measurements presented in Figs. 2 and 3(a), provide strong constraints that the combined sources of background, scale as $1/N_{ch}$ over the full centrality span. The background estimates were used to extract $f_{CME}$ values for Au+Au, (Fig. 3 (c)) Ru+Ru and Zr+Zr collisions respectively. They indicate non-negligible $f_{CME}$ values that vary with centrality. In mid-central collisions, $f_{CME} \sim 27\%$ for Au+Au collisions, which is roughly a factor of two larger than the values for Ru+Ru and Zr+Zr. Within the uncertainties, no significant difference between the values for Ru+Ru and Zr+Zr was observed, suggesting that $\Delta \gamma/v_2$ is sensitive to CME-driven charge separation in Ru+Ru and Zr+Zr collisions but may be insensitive to the signal difference between them [17].

In summary, the scaling properties of the $R_{\Psi_2}(\Delta S)$ and the $\Delta \gamma$ correlators have been used to characterize the CME in several colliding systems at RHIC and the LHC. The results for $p+Au$ and $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV and $p+Pb$ ($\sqrt{s_{NN}} = 5.02$ TeV) and Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV, scales as $1/N_{ch}$ consistent with background-driven charge separation. However, the results for Au+Au, Ru+Ru and Zr+Zr collisions ($\sqrt{s_{NN}} = 200$ GeV) show scaling violations which indicate a CME-driven contribution in the presence of significant background. In mid-central collisions, $f_{CME} \sim 27\%$ for Au+Au collisions and approximately a factor of two smaller in Ru+Ru and Zr+Zr collisions but with similar magnitudes for the two isobars.
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