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

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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 $\sqrt{s_{\rm NN}} = 200$ GeV, and in p+Pb ($\sqrt{s_{\rm NN}} = 5.02$ TeV) and Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ and 2.76 TeV. The results for p+Au, d+Au, p+Pb, and Pb+Pb collisions, show the $1/{\rm N_{ch}}$ 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 $\vec{J}_V = \frac{N_c e\vec{B}}{2\pi^2}\mu_A$, along the $\vec{B}$-field, i.e., perpendicular to the reaction plane; N_c is the color factor, and μ_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]:

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

where $\Delta\phi = \phi - \Psi_{\rm RP}$ 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 $\mathcal{P}$ and $\mathcal{CP}$ symmetry of QCD. However, their fluctuation and/or variance $\tilde{a}_1 = \left\langle a_1^2 \right\rangle^{1/2}$ can be measured with charge-sensitive correlators such as the γ-correlator [3] and the $R_{\Psi_2}(\Delta S)$ correlator [4].

The γ-correlator measures charge separation as: $\gamma_{\alpha\beta} = \left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_2\right)\right\rangle$, $\Delta\gamma = \gamma_{\rm OS} - \gamma_{\rm SS}$, where Ψ_2 is the azimuthal angle of the 2$^{\rm nd}$-order event plane which fluctuates

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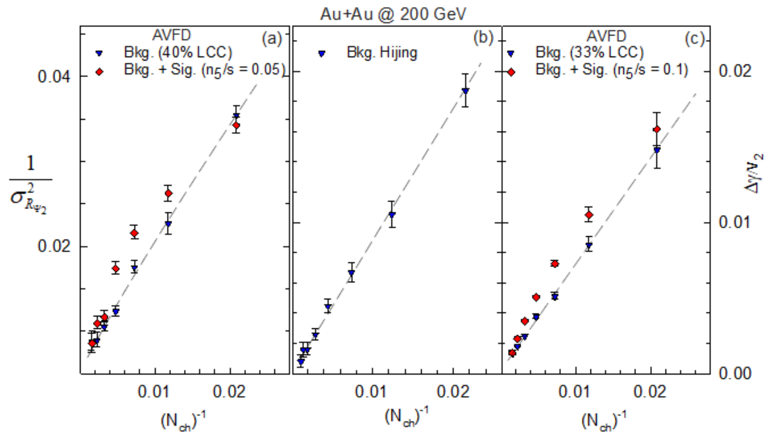

Figure 1. $\sigma^{-2}_{R_{\Psi_2}}$ vs. $1/\mathrm{N_{ch}}$ (a) and $\Delta\gamma/v_2$ vs. $1/\mathrm{N_{ch}}$ (b) and (c) for simulated Au+Au collisions at $\sqrt{s}_{\mathrm{NN}}$ = 200 GeV. The results for $\sigma^{-2}_{R_{\Psi_2}}$ and $\Delta\gamma/v_2$ from the AVFD model are shown for background and for signal + background as indicated. The Hijing model results are only shown for the background. The dashed lines represent linear fits to the background values.

about the RP, ϕ denote the particle azimuthal emission angles, α, β 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 Ψ_2 via the ratio: $R_{\Psi_2}(\Delta S) = C_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S)$, where $C_{\Psi_2}(\Delta S)$ and $C^{\perp}_{\Psi_2}(\Delta S)$ are correlation functions that quantify charge separation ΔS, 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 $C^{\perp}_{\Psi_2}(\Delta S)$ 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 $\sigma^{-2}_{R_{\Psi_2}}$ are used to quantify the charge separation [4].

In this work, we use model simulations to chart the scaling properties of $\sigma^{-2}_{R_{\Psi_2}}$ 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 $\sigma^{-2}_{R_{\Psi_2}}$ 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 $1/\mathrm{N_{ch}}$ – 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; $\Delta\gamma/v_2 = a + b/(\mathrm{N_{ch}})^{1-\mathrm{c}}$, and $\sigma^{-2}_{R_{\Psi_2}} = a' + b'/(\mathrm{N_{ch}})^{1-\mathrm{c}'}$, 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 $c \sim 0$ the $1/\mathrm{N_{ch}}$ 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: $f^{\Delta\gamma}_{\mathrm{CME}} = [\Delta\gamma/v_2(Sig.+Bkg.) - \Delta\gamma/v_2(Bkg.)]/[\Delta\gamma/v_2(Sig.+Bkg.)]$, $f^{R}_{\mathrm{CME}} = [\sigma^{-2}_{R_{\Psi_2}}(Sig.+Bkg.) - \sigma^{-2}_{R_{\Psi_2}}(Bkg.)]/[\sigma^{-2}_{R_{\Psi_2}}(Sig.+Bkg.)]$. The scaling patterns in Fig. 1 suggest that the observation of $1/\mathrm{N_{ch}}$ scaling for the experimental $\sigma^{-2}_{R_{\Psi_2}}$ 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 $1/\mathrm{N_{ch}}$ scaling would indicate the CME-driven contribution. Figs. 1 (a) and (c) also indicate comparable background and signal + background $\sigma^{-2}_{R_{\Psi_2}}$ 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 $\vec{B}$ in central collisions and the enhanced de-correlation between the event plane and the $\vec{B}$-field in peripheral collisions. Since the background dominates in central and peripheral collisions, the $\sigma^{-2}_{R_{\Psi_2}}$ and $\Delta\gamma/v_2$ measurements for these collisions can be leveraged with $1/\mathrm{N_{ch}}$ 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.

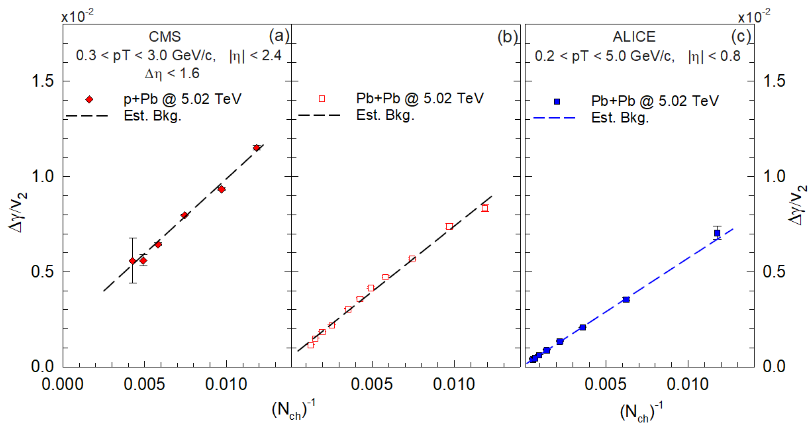

Figure 2. $\Delta\gamma/v_2$ vs. $1/\mathrm{N_{ch}}$ for p+Pb (a) and Pb+Pb [(c) and (d)] collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The dashed lines indicate an estimate of the background. The data are taken from Refs. [12, 13, 15].

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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. They indicate that $\Delta\gamma/v_2$ essentially scales as $1/\mathrm{N_{ch}}$ ($c \approx 0$), 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 $1/\mathrm{N_{ch}}$. Note as well that the CME contribution is negligible in $p(d)$+A collisions because of significant reductions in $\vec{B}$, and the sizable de-correlation between the event plane and the $\vec{B}$-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 $1/\mathrm{N_{ch}}$ scaling of the background.

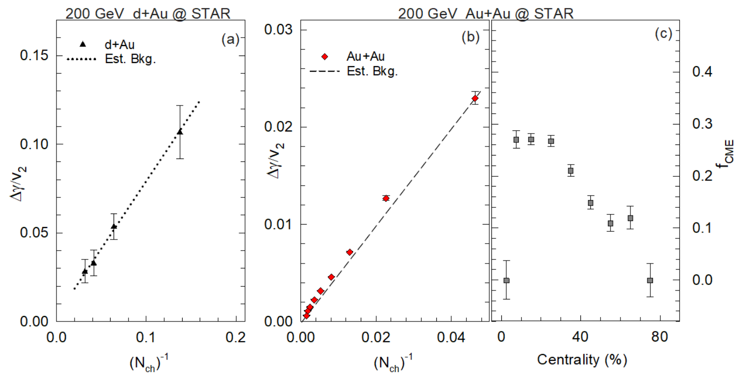

Figure 3. $\Delta\gamma/v_2$ vs. $1/\mathrm{N_{ch}}$ [(a) and (b)] and f_{CME} vs. centrality (c) for d+Au and Au+Au collisions at $\sqrt{s}_{\mathrm{NN}}$ = 200 GeV. The dotted and dashed lines indicate an estimate of the background contributions. The data are taken from Refs. [7, 9**?**].

The scaling results for Au+Au collisions at $\sqrt{s}_{\mathrm{NN}}$ = 200 GeV are shown in Fig. 3. The $1/\mathrm{N_{ch}}$ 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 $1/\mathrm{N_{ch}}$ scaling. In contrast to d+Au, the results for Au+Au (Fig. 3(b)) show visible indications of a violation ($c > 0$) to the $1/\mathrm{N_{ch}}$ 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 $1/\mathrm{N_{ch}}$ 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 $1/\mathrm{N_{ch}}$ 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, $f_{\mathrm{CME}} \sim 27\%$ 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 $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV and p+Pb ($\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV) and Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 and 2.76 TeV, scales as $1/\mathrm{N_{ch}}$ consistent with background-driven charge separation. However, the results for Au+Au, Ru+Ru and Zr+Zr collisions ($\sqrt{s_{\mathrm{NN}}}$ = 200 GeV) show scaling violations which indicate a CME-driven contribution in the presence of significant background. In mid-central collisions, $f_{\mathrm{CME}} \sim 27\%$ 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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