Scaling properties of the $\Delta \gamma$ correlator and their implication for detection of the chiral magnetic effect in heavy-ion collisions

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The scaling properties of the $\Delta \gamma$ correlator, inferred from the Anomalous Viscous Fluid Dynamics (AVFD) model, 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 indicate that the values of the quotient $\Delta \gamma/v_2$ with the elliptic flow coefficient $v_2$ for $p+Au$, $d+Au$, $p+Pb$, and $Pb+Pb$ collisions, scale as $1/N_{ch}$ consistent with background-driven charge separation. By contrast, the $\Delta \gamma/v_2$ values for $Ru+Ru$, $Zr+Zr$, and $Au+Au$ collisions show scaling violations consistent with the presence of background plus a CME-driven contribution. Quantifying this CME-driven component indicates that in mid-central collisions, the fraction of the measured $\Delta \gamma/v_2$ attributable to the CME is approximately 27% for $Au+Au$ and roughly a factor of two smaller for $Ru+Ru$ and $Zr+Zr$, which show similar magnitudes.

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In relativistic ion-ion collisions, metastable domains of gluon fields with non-trivial topological configurations \cite{1,2} can form in the magnetized chiral relativistic quark-gluon plasma (QGP) \cite{3,7} produced in the collisions. The magnetic field ($\vec{B}$) is generated by the incoming ions at early times \cite{8,9} during the collision. The interaction of chiral quarks with the gluon fields can lead to an imbalance in left- and right-handed quarks, which violates local parity ($P$) symmetry \cite{2}. This chirality imbalance [in the magnetized plasma] leads to an electric current

$$\vec{J}_V = \frac{N_c e \vec{B}}{2\pi} \mu_A, \quad \text{for } \mu_A \neq 0,$$

(1)

along the $\vec{B}$-field [perpendicular to the reaction plane], resulting in a final-state charge separation phenomenon, known as the chiral magnetic effect (CME) \cite{3}. Here $N_c$ is the color factor and $\mu_A$ is the axial chemical potential that quantifies the axial charge asymmetry or imbalance between right- and left-handed quarks in the plasma \cite{10-13}.

The charge separation can be quantified via measurements of the first $P$-odd sine term $a_1$, in the Fourier decomposition of the charged-particle azimuthal distribution $\text{(1)}$:

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

(2)

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 the $P$-odd coefficients $a_1$, is not possible due to the strict global $P$ and $CP$ symmetry of QCD. However, their fluctuation and/or variance $a_1 = \langle a_1^2 \rangle^{1/2}$ can be measured with charge-sensitive correlators such as the $\gamma$-correlator $\text{(1)}$ and the $R_{\gamma}(\Delta S)$ correlator $\text{(15-18)}$.

The $\gamma$-correlator measures charge separation as:

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle, \quad \Delta \gamma = \gamma_{OS} - \gamma_{SS},$$

(3)

where $\Psi_2$ is the azimuthal angle of the 2$^{nd}$-order event plane which fluctuates 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. The three-particle correlation method $\text{(14, 19, 20)}$ can also be used to evaluate the $\gamma$-correlator as:

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_\kappa) \rangle / v_{2,\kappa}, \quad \Delta \gamma = \gamma_{OS} - \gamma_{SS},$$

(3)

where $\phi_\kappa$ is the azimuthal angle of a third, charge-inclusive particle $\kappa$ which serves as a measure of $\Psi_2$. The elliptic flow coefficient $v_{2,\kappa}$ is a resolution factor that accounts for the sizable fluctuations associated with determining $\Psi_2$ with a single particle.

Experimental measurements indicate significant $\Delta \gamma$ in $p+Au$, $d+Au$, $Ru+Ru$, $Zr+Zr$ and $Au+Au$ collisions at RHIC $\text{(19-25)}$, and in $p+Pb$ and $Pb+Pb$ collisions at the LHC $\text{(26-30)}$. However, in addition to a possible CME-driven contribution, a significant charge-dependent background (Bkg.) contributes to the $\Delta \gamma$ measurements $\text{(14, 31-35)}$

$$\Delta \gamma \approx \Delta \gamma^{CME} + b \frac{v_2}{N_{ch}},$$

(4)

where $bN_{ch}$ gives an estimate of the charge-dependent non-flow background; $b$ is a proportionality constant and $v_2$ and $N_{ch}$ are the elliptic flow coefficient and the mean number of charge particles at a given collision centrality of interest. This background has hampered the extraction of the CME-driven component $\Delta \gamma^{CME}$ from the

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$\Delta \gamma$ measurements. However, Eq. 4 indicates that $\Delta \gamma / v_2$ for the background contribution scales as $1/N_{ch}$ and finite values of $\Delta \gamma^\text{CME}$ should lead to a violation of this $1/N_{ch}$ dependence, suggesting that the scaling properties for $\Delta \gamma / v_2$ measurements can provide new constraints for background estimates and hence, reliable $\Delta \gamma^\text{CME}$ extraction.

In this work, we use the AVFD model [36, 37] to chart the scaling patterns of $\Delta \gamma / v_2$ for the background and signal + background in $A+A$ collisions. We then leverage these scaling patterns to estimate $\Delta \gamma^\text{CME}$ from the previously published data for $p+Au$, $d+Au$, $Ru+Ru$, $Zr+Zr$ and $Au+Au$ collisions at RHIC [17, 25] and $p+Pb$ and $Pb+Pb$ collisions at the LHC [26, 29]. The $\Delta \gamma^\text{CME}$ contribution is expected to be negligible in $p(d)+A$ collisions because the $\vec{B}$-field is significantly reduced and the event plane is essentially uncorrelated with the impact parameter or the $\vec{B}$-field [38, 40] in these collisions. The charge-dependent non-flow background for these systems are also large and multifaceted, suggesting that they can give insight on whether the background induces violations to $1/N_{ch}$ scaling. Thus, the $\Delta \gamma / v_2$ scaling patterns for $p(d)+A$ collisions provide a good validation benchmark for the background.

The AVFD model provides an essential benchmark for evaluating the interplay between possible CME- and background-driven charge separation in actual data. The model simulates charge separation resulting from the combined effects of the CME and the background [36, 37]. In brief, the Event-by-Event version of the model (Eby-E AVFD) uses Monte Carlo Glauber initial conditions to simulate the evolution of fermion currents in the QGP, in concert with the bulk fluid evolution implemented in the VISHNU hydrodynamic code [41], followed by a URQMD hadron cascade stage. Background-driven charge-dependent correlations result from local charge conservation (LCC) on the freeze-out hypersurface and resonance decays. A time-dependent magnetic field $B(\tau) = \frac{B_0}{1+(\tau/\tau_B)^2}$, acting in concert with a nonzero initial axial charge density $n_{5/s}$, is used to generate a CME current (embedded in the fluid dynamical equations), leading to a charge separation along the magnetic field. The peak values $B_0$, obtained from event-by-event simulations [42], are used with a relatively conservative lifetime $\tau_B = 0.6$ fm/c. The initial axial charge density, which results from gluonic topological charge fluctuations, is estimated based on the strong chromo-electromagnetic fields in the early-stage glasma. The present work uses the input scaling parameters for $n_{5/s}$ and an LCC fraction to regulate the magnitude of the CME- and background-driven charge separation.

Simulated AVFD events were generated for varying degrees of signal and background for a broad set of centrality selections in $A+A$ collisions to chart the scaling properties of $\Delta \gamma / v_2$.

The centrality dependence of the $\Delta \gamma / v_2$ values obtained from AVFD events is summarized for $Au+Au$ collisions in Fig. 1(a). To highlight the scaling property of the background (Bkg.) $\Delta \gamma / v_2$ is plotted vs. $1/N_{ch}$. The solid triangles in Fig. 1(a) show that the background scales as $1/N_{ch}$ - the expected trend for charge-dependent non-flow correlations. By contrast, the $\Delta \gamma / v_2$ values for signal (Sig.) + background indicate positive deviations from the $1/N_{ch}$ scaling observed for the background. This apparent scaling violation gives a direct signature of the CME-driven contributions to the charge separation. It can be quantified via the fraction of the total $\Delta \gamma / v_2$ attributable to the CME as:

$$f_{\text{CME}} = \frac{\Delta \gamma / v_2(\text{Sig.} + \text{Bkg.})}{\Delta \gamma / v_2(Bkg.)}. \quad (5)$$

This fraction is shown as a function of $1/N_{ch}$ in Fig. 1(b). The figure indicates the value $f_{\text{CME}} \approx 30\%$ for $30-40\%$ central collisions, which is a good benchmark of the sensitivity of the $\Delta \gamma$ correlator to CME-driven charge separation of this signal level ($n_{5/s} = 0.1$) in the presence of charge-dependent background (LCC = 33\%) in Au+Au collisions. Fig. 1(b) also shows that the $f_{\text{CME}}$ values peak in mid-central collisions but reduce to approximately zero at large and small $N_{ch}$ (i.e., in central and peripheral collisions), indicating comparable background and signal + background $\Delta \gamma / v_2$ values for these centralities.

The scaling patterns in Fig. 1(a) suggest that the observation of $1/N_{ch}$ scaling for the experimental $\Delta \gamma / v_2$ measurements would be a strong indication for background-driven charge separation with little room for
a CME contribution. However, the observation of a violation of this $1/N_{ch}$ scaling could be an indication for the CME-driven contribution $\Delta \gamma_{\text{CME}}$ (cf. Eq. 4). Fig. 1 also indicates comparable background and signal + background $\Delta \gamma/v_2$ values in central and peripheral collisions, suggesting that the influence of background-driven charge separation dominates over that for the CME-driven contributions in these collisions. This dominance, which results from a significant reduction in the $\vec{B}$-field in central collisions and the de-correlation between the event plane and the $\vec{B}$-field in peripheral collisions, suggests that the $\Delta \gamma/v_2$ measurements for peripheral and central collisions can be leveraged with $1/N_{ch}$ scaling to obtain a quantitative estimate of the background over the entire 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 [19–21, 23–25], and $p+Pb$ and $Pb+Pb$ collisions at the LHC [27–30] 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 $\sqrt{s_{NN}} = 5.02$ TeV. They indicate that $\Delta \gamma/v_2$ essentially scales as $1/N_{ch}$. The results for $p+Pb$ collisions are in line with the expected negligible values for $\Delta \gamma_{\text{CME}}$ in these collisions (cf. Eq. 4). They also indicate that possible additional sources of non-flow, which should be much larger for $p+Pb$ than $Pb+Pb$, do...

FIG. 2. $\Delta \gamma/v_2$ vs. $1/N_{ch}$ for $p+Pb$ (a) and $Pb+Pb$ [(c) and (d)] collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The dashed lines indicate an estimate of the background contribution. The data are taken from Refs. [28–30].

FIG. 3. $\Delta \gamma/v_2$ vs. $1/N_{ch}$ for $q_2$-selected events in $Pb+Pb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The dashed lines indicate an estimate of the background contribution. The data are taken from Ref. [27].
FIG. 4. $\Delta\gamma/v_2$ vs. $1/N_{ch}$ [(a) and (b)] and $f_{CME}$ vs. centrality (c) for $d+Au$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The dotted and dashed lines indicate an estimate of the background contributions. The $f_{CME}$ values in (c) characterize the fraction of the charge separation which is CME-driven (cf. Eq. 5). The data are taken from Refs. [22, 24, 44].

FIG. 5. $\Delta\gamma/v_2$ vs. $1/N_{ch}$ [(a) and (c)] and $f_{CME}$ vs. centrality [(b) and (d)] for $Ru+Ru$ and $Zr+Zr$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed lines indicate an estimate of the background contributions. The $f_{CME}$ values in (b) and (d) characterize the fraction of the charge separation which is CME-driven (cf. Eq. 5). The data are taken from Ref. [25].

not influence the $1/N_{ch}$ scaling. The scaling patterns in Figs. 2(b) and (c), also suggest negligible $\Delta\gamma_{CME}$ contributions in these Pb+Pb collisions. A similar conclusion is indicated by the results in Fig. 3 for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. These measurements were obtained with event-shape selection via fractional cuts on the distribution of the magnitude of the $q_2$ flow vector [45]. The $q_2$ selections are indicated in the figure.

The scaling results for RHIC collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Figs. 4 and 5. The patterns for $d+Au$ collisions reflect the $1/N_{ch}$ scaling observed for $p+Pb$ collisions (cf. Fig. 2(a)) and confirms the expectation that $\Delta\gamma_{CME}$ is negligible for $p(d)+A$ collisions. Similar scaling properties were observed for $p+Au$ collisions (not shown), albeit with less statistical significance. In contrast to $d+Au$, the results for $Au+Au$ (Fig. 4(b)) $Ru+Ru$ (Fig. 5(a)) and $Zr+Zr$ (Fig. 5(c)) show visible indications of a violation of the $1/N_{ch}$ scaling observed for background-driven charge separation in $p(d)+A$ collisions. The scaling violation is similar to that observed for signal + background in Fig. 1(a), suggesting an unambiguous non-negligible $\Delta\gamma_{CME}$ contribution to the measured $\Delta\gamma$ in $Au+Au$, $Ru+Ru$, and $Zr+Zr$ collisions.

We estimate the magnitude of the respective $\Delta\gamma_{CME}$ contributions via $f_{CME}$ (cf. Eq. 5) following an estimate of the background contributions to $\Delta\gamma/v_2$. As discussed, the background estimate is obtained by leveraging the $\Delta\gamma/v_2$ measurements for peripheral and cen-
central collisions with 1/Nch scaling; note Figs. 1(a), 2(a) and 3(a). These estimates are indicated by the dashed lines in Figs. 3(b), 5(a) and 5(c) respectively. The resulting fCME values are plotted as a function of centrality in Figs. 3(c), 3(b) and 3(d) for Au+Au, Ru+Ru and Zr+Zr collisions respectively. They indicate non-negligible fCME values that vary with centrality. In mid-central collisions, fCME ∼ 27% for Au+Au collisions, which is roughly a factor of two larger than the values for Ru+Ru and Zr+Zr. Note as well that within the indicated uncertainties, there is no significant difference between the fCME values for Ru+Ru and Zr+Zr suggesting that the ∆γ correlator is sensitive to CME-driven charge separation in Ru+Ru and Zr+Zr collisions but may be insensitive to the signal difference between them. An estimate of the expected signal difference from the fCME magnitudes in Fig. 3(b) indicate only a value of ∼ 1.3%.

In summary, we have used the scaling properties of the ∆γ correlator to characterize a possible chirally-magnetically-driven charge separation in several colliding systems at RHIC and the LHC. We find that ∆γ/v2 for p+Au and d+Au collisions at √sNN = 200 GeV and p+Pb (√sNN = 5.02 TeV) and Pb+Pb collisions at √sNN = 5.02 and 2.76 TeV, scales as 1/Nch consistent with background-driven charge separation. In contrast, ∆γ/v2 for Ru+Ru, Zr+Zr and Au+Au collisions show scaling violations consistent with significant background plus a CME-driven contribution ∆γCME. Quantifying this CME-driven component indicates that the fraction of the total ∆γ/v2 attributable to the CME in mid-central collisions is about 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 iso-

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