Charge-dependent pair correlations relative to a third particle in $p+Au$ and $d+Au$ collisions at RHIC

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Quark interactions with topological gluon configurations can induce chirality imbalance and local parity violation in quantum chromodynamics. This can lead to electric charge separation along
the strong magnetic field in relativistic heavy-ion collisions – the chiral magnetic effect (CME). We report measurements by the STAR collaboration of a CME-sensitive observable in \( p+Au \) and \( d+Au \) collisions at 200 GeV, where the CME is not expected, using charge-dependent pair correlations relative to a third particle. We observe strong charge-dependent correlations similar to those measured in heavy-ion collisions. This bears important implications for the interpretation of the heavy-ion data.

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**INTRODUCTION**

In quantum chromodynamics, interactions of massless quarks with fluctuating topological gluon fields are predicted to induce chirality imbalance and parity violation in a local domain \([1,3]\). This chirality imbalance can lead to an electric charge separation in the presence of a strong magnetic field \((\vec{B})\), a phenomenon known as the chiral magnetic effect (CME) \([4,9]\). Such a strong \( \vec{B} \)-field may be available in relativistic heavy-ion collisions, generated by the incoming protons at early times \([8,10]\). Extensive theoretical and experimental efforts have been devoted to the search for the CME-induced charge separation along \( \vec{B} \) in heavy-ion collisions \([11,13]\).

The commonly used observable to search for charge separation in heavy-ion collisions is the three-point azimuthal correlator \([1,4]\):

\[
\gamma \equiv \cos(\phi_{\alpha} + \phi_{\beta} - 2\psi), \tag{1}
\]

where \( \phi_{\alpha} \) and \( \phi_{\beta} \) are the azimuthal angles of particles \( \alpha \) and \( \beta \), respectively. In Eq. (1), \( \psi \) is the azimuthal angle of the impact parameter vector. In heavy-ion collisions, it is called the reaction plane (spanned by the impact parameter vector). In order to remove the charge independent background \([17,18]\), such as that due to momentum conservation, the correlation difference variable is used,

\[
\Delta\gamma \equiv \gamma_{OS} - \gamma_{SS}, \tag{3}
\]

where \( \gamma_{OS} \) stands for the correlation of opposite-sign (OS) pairs (\( \alpha \) and \( \beta \) have opposite-sign electric charges) and \( \gamma_{SS} \) for that of the same-sign (SS) pairs (\( \alpha \) and \( \beta \) have same-sign electric charge).

Significant \( \Delta\gamma \) is indeed observed in heavy-ion collisions at RHIC \([17,18,20,21]\), and at LHC \([22,25]\). However, a decisive answer regarding the existence, or not, of the CME is still under debate. The main difficulty in interpreting the \( \Delta\gamma \) observable as originated from the CME is the possibility of significant charge-dependent background contributions, such as those from resonance decays \([14,26,30]\). This is because the \( \Delta\gamma \) variable is ambiguous between an OS pair from the CME back-to-back perpendicular to \( \psi_2 \) (charge separation) and an OS pair from a resonance decay along \( \psi_2 \) (charge conservation). There are more particles/resonances along the \( \psi_2 \) (or the particle \( c \)) direction than perpendicular to it, an effect quantified by the elliptical anisotropy parameter \( v_{2,\text{res}} \).

Equation (2) is valid and \( \Delta\gamma \) would be a good measure of the CME only under the assumption that all particles (including the CME-related particles) are correlated to a global plane \( \psi_2 \), but intrinsically uncorrelated among themselves. When \( \alpha \) and \( \beta \) are intrinsically correlated, then \( \Delta\gamma \) would contain a background \((\Delta\gamma_{\text{bkgd}})\), arising from the coupling of this elliptical anisotropy and the intrinsic decay correlation and is expected to take the following form \([14,26,30]\):

\[
\Delta\gamma_{\text{bkgd}} \propto \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\phi_{\text{res}}) \rangle v_{2,\text{res}}. \tag{4}
\]

Other possible backgrounds include three-particle nonflow correlations, where the correlation of particle \( \alpha \), \( \beta \) with particle \( c \) is also of nonflow nature. Moreover, the estimate of \( v_{2,c} \) via two-particle correlations may also be affected by short-range nonflow correlations. These effects are likely dominant for very low multiplicity events because they are not sufficiently diluted by multiplicity combinatorics. Nevertheless, the factorization relation in Eq. (2) is still expected to approximately hold, regardless of the nature of the background correlations \([31]\).

In non-central heavy-ion collisions, the participant plane, although fluctuating \([16]\), is generally aligned with the reaction plane, thus generally perpendicular to \( \vec{B} \). In proton-nucleus collisions, however, the participant plane is determined purely by geometry fluctuations, and thus is essentially uncorrelated with the impact parameter or the \( \vec{B} \) direction \([24,32,33]\). A recent study, considering the fluctuating size of the proton, suggests a small but non-zero correlation \([33]\). Therefore, CME-induced \( \Delta\gamma \) with respect to the \( \psi_2 \) is significantly suppressed in proton-nucleus collisions compared to possible signals from heavy-ion collisions \([33]\). Background
correlations aforementioned is expected to be present in proton-nucleus collisions as well. These correlations are propagated to the three-particle correlator via correlations with respect to particle $c$, not directly to the impact parameter or the $B$ direction. Thus, the backgrounds in proton-nucleus collisions contribute in a similar fashion as those in heavy-ion collisions. Indeed, a large $\Delta \gamma$ signal was observed in $p+Pb$ collisions at the LHC, similar to that in Pb+Pb collisions. This challenged the CME interpretation of the heavy-ion data [24].

It is possible that the CME would decrease as collision energy increases, due to the more rapidly decaying $B$ at higher energies [8, 34]. Hence, the similarity between $p+Pb$ and $Pb+Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the LHC may be expected, and the situation at RHIC could be different [11]. Here we report $\Delta \gamma$ measurements by the STAR experiment at RHIC in small-system $p+Au$ and $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

EXPERIMENT AND DATA ANALYSIS

The data reported here were taken by the STAR experiment in 2003 ($d+Au$) and 2015 ($p+Au$). The STAR experiment apparatus is described elsewhere [35]. Minimum bias (MB) triggers were used for both data taking periods. For $d+Au$ [36], the MB trigger required at least one beam-rapidity neutron in the Zero Degree Calorimeter (ZDC) [37] in the Au beam direction. For $p+Au$, the MB trigger data used in this analysis was defined as a coincidence between the two Vertex Position Detectors (VPDs) [38].

The detectors relevant to this analysis are the cylindrical Time Projection Chamber (TPC) [39, 40] residing inside an approximately uniform magnetic field of 0.5 Tesla along the beam direction ($z$). Charged particles traversing the chamber ionize the TPC gas. The ionization electrons drift towards the TPC endcaps in a uniform electric field, provided by the high voltage on the TPC central membrane. The avalanche electrons are collected by the pad planes, and together with the drift time information, provide three-dimensional space points of the ionization called “hits”.

Trajectories are reconstructed from those hits; at least 10 hits are required for a valid track. The interaction’s primary vertex is reconstructed from charged particle tracks. Tracks with the distance of closest approach (DCA) to the primary vertex within 3 cm are considered primary tracks. The data are reported as a function of the efficiency corrected charged particle multiplicity density $dN_{ch}/d\eta$ at mid-rapidity [41]. The efficiency is estimated via the STAR standard embedding procedure, which is $\sim 93\%$ in $p+Au$ and $d+Au$ collisions.

In this analysis, events with primary vertices within 30 cm in $p+Au$ (50 cm in $d+Au$) longitudinally and 2 cm in $p+Au$ (3.5 cm in $d+Au$) transversally from the geometrical center of the TPC are used. To ensure high quality of primary particles, further selections are applied to require tracks with at least 20 hits and DCA less than 2 cm. Split tracks are removed by requiring the number of hits over the maximum number of possible hits to be greater than 0.52 [12]. In the $p+Au$ analysis, where VPD detectors and Time-of-Flight (TOF) detector [43] are available, the primary vertex is required to match with the VPD’s measured vertex within 6 cm, and primary tracks are required to match with the TOF detector in order to reduce the pile-up tracks.

Tracks in the full TPC acceptance ($|\eta| < 1$, reducing to $|\eta| < 0.9$ in case of TOF matched tracks in $p+Au$) with transverse momentum $p_T$ from 0.2 to 2.0 GeV/c are used for all three particles in the three-particle correlator of Eq. [2]. The cumulant method is used to compute $\gamma$, where the calculation loops over the $\alpha$ and $\beta$ particles, and the particle $c$ is handled by the cumulant of the remaining particles except $\alpha$ and $\beta$. No $\eta$ gap is applied between any pair among the three particles as in Refs. [17, 18]. The $v_{2,c}$ is obtained by the two-particle cumulant [44]. To gauge the nonflow effects, various $\eta$ gaps of 0, 0.5, 1.0 and 1.4 are applied. The $p_T$-dependent TPC tracking efficiency is not corrected for the $\gamma$ correlator as in Refs. [17, 18], and this effect is included in the systematic uncertainties. The detector non-uniform azimuthal acceptance effect is corrected by the recentering method as a function of $p_T$ [45, 46].

SYSTEMATIC UNCERTAINTIES

The systematic uncertainties are estimated as follows. The required minimum number of points is varied from 20 to 25. The DCA of tracks is varied from 2 cm to 3 cm. The $p_T$ range of the particle $c$ is varied from 0.2-2 GeV/c to 0.2-5 GeV/c. The difference between the results from events with positive and negative reconstructed $z$ coordinate of primary vertex is $\sim 2\%$. The $p_T$-dependent TPC tracking efficiency correction introduces a $\sim 1\%$ difference. $p_T$-independent azimuthal non-uniformity recentering correction is also studied. The TOF detector acceptance is limited to $|\eta| < 0.9$, and this causes a $\sim -6\%$ (single sided) effect in $p+Au$. The systematic uncertainties obtained by various cuts and sources are added in quadrature. These are plotted in the figures as brackets. The horizontal brackets indicate the systematic uncertainty of the $dN_{ch}/d\eta$. The vertical brackets indicate the systematic uncertainty of the correlator. Total systematic uncertainty of the $\Delta \gamma$ is $\sim 9\%$ in $p+Au$ and $d+Au$ (Table I). Total systematic uncertainty of the $dN_{ch}/d\eta$ is $\sim 15\%$ in $p+Au$ and is $\sim 7\%$ in $d+Au$. 
TABLE I. The systematic uncertainties of the $\Delta\gamma$ correlator in $p+Au$ and in $d+Au$ collisions.

| source       | $p+Au$ | $d+Au$ |
|--------------|--------|--------|
| dca & nHits  | ±5%    | ±8%    |
| $p_\gamma(c)$| ±0%    | ±1%    |
| $V_c$        | ±2%    | ±2%    |
| $p_T$-dependent efficiency | ±1% | ±1% |
| $p_T$-independent non-uniformity | ±5% | ±4% |
| TOF acceptance | −6% | −    |
| total        | ±9%    | ±9%    |

RESULTS AND DISCUSSIONS

Figure 1 shows the $\gamma_{SS}$ and $\gamma_{OS}$ results as functions of multiplicity in $p+Au$ and $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. For comparison, the corresponding $Au+Au$ results [17, 18, 20] are also shown. The dashed lines represent the results with $v_{2,c}$ using different $\eta$ gaps of 0, 0.5 and 1.4 in $p+Au$ and $d+Au$ collisions. The results with $v_{2,c}$ using $\eta$ gaps of 1.0 in $p+Au$ and $d+Au$ collisions are plotted as solid lines. The results show that the variation from different $\eta$ gaps is large but tends to converge towards high multiplicity. The $\gamma_{SS}$ and $\gamma_{OS}$ results seem to follow a decreasing trend with increasing multiplicity in all systems.

If indeed dominated by background contributions, the $\Delta\gamma$ may be proportional to the average $v_2$ of the background sources, as represented by Eq. 1. The $v_2$ of the background sources likely scale with the $v_2$ of the final-state particles that are measured. The background should also be proportional to the number of background sources, and because $\Delta\gamma$ is a pair-wise average, the background is also inversely proportional to the total number of pairs. As the number of background sources likely scales with $dN_{ch}/d\eta$, thus $\Delta\gamma$ approximately scales with $v_2/dN_{ch}/d\eta$. To gain more insight, a scaled $\Delta\gamma$ observable is introduced:

$$\Delta\gamma_{scaled} = \Delta\gamma \times dN_{ch}/d\eta/v_2.$$  (5)

Since in our analysis there is no distinction between particles $\alpha$, $\beta$ and $c$ except the electric charge, the $v_2$ in Eq. 1 is the same as $v_{2,c}$. Figure 3 shows the measured $v_2$ by the two-particle cumulant method with various $\eta$ gaps as a function of multiplicity in $p+Au$, $d+Au$ collisions, together with results from $Au+Au$ [17, 18] collisions. The results show that $v_2$ is large in $p+Au$ and $d+Au$ collisions, and comparable to $Au+Au$ results. HIJING [17] simulation studies of $p+Au$ and $d+Au$ collisions suggest...
significant contribution of nonflow correlations to \( v_2 \) at very low multiplicities. Evidence of contribution to \( v_2 \) from collective flow has also been observed at RHIC and the LHC from long-range particle correlations in small systems, especially at higher multiplicity [48,52].

Figure 3 shows the measured two-particle cumulant \( v_2(2) \) with \( \eta \) gap of 1.0 as a function of multiplicity in \( p+Au \) and \( d+Au \) collisions, compared to that in \( Au+Au \) collisions [17] [18]. The data points connected by solid lines are measured using \( \Delta \eta \) gap of 1.0 in \( v_2(2) \). Results with \( \eta \) gaps of 0, 0.5 and 1.4 are shown in dash lines.

CONCLUSIONS

Experimental measurements of \( \Delta \gamma \) in heavy–ion collisions suffer from major backgrounds. It is expected that the \( \Delta \gamma \) correlator from small-system \( p+Au \) and \( d+Au \) collisions will be dominated by background correlations, as CME-induced contributions would be strongly suppressed due to the random orientations of the magnetic field and the participant plane. We reported here measurements of large \( \Delta \gamma \) magnitudes in \( p+Au \) and \( d+Au \) collisions, comparable to the values previously reported for peripheral \( Au+Au \) collisions at similar multiplicities \( (dN_{ch}/d\eta) \). This is similar to the observation at the LHC, where a large \( \Delta \gamma \) signal is observed in \( p+Pb \) collisions and is comparable to that in \( Pb+Pb \) collisions. The scaled quantity, \( \Delta \gamma \times dN_{ch}/d\eta/v_2 \), is approximately constant over \( dN_{ch}/d\eta \), although within large systematic uncertainties. Since \( p+Au \) and \( d+Au \) results are dominated by background contributions, the approximate \( dN_{ch}/d\eta \)-independent \( \Delta \gamma_{\text{scaled}} \) over the wide range of multiplicity in \( Au+Au \) collisions is consistent with the background scenario. Future measurements with larger \( \eta \) gaps, especially utilizing upgraded forward detectors, have the potential to significantly suppress short-range background correlations. Those studies will help further to understand the background behavior and differentiate it from the possible CME signal.

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![FIG. 3. The measured two-particle cumulant \( v_2(2) \) with \( \eta \) gap of 1.0 as a function of multiplicity in \( p+Au \) and \( d+Au \) collisions, compared to that in \( Au+Au \) collisions [17] [18]. The data points connected by solid lines are measured using \( \Delta \eta \) gap of 1.0 in \( v_2(2) \). Results with \( \eta \) gaps of 0, 0.5 and 1.4 are shown in dash lines.](image)

![FIG. 4. The \( \Delta \gamma \times dN_{ch}/d\eta/v_2 \) in \( p+Au \) and \( d+Au \) collisions as a function of multiplicity, compared to that in \( Au+Au \) collisions [17] [18] [20]. The data points connected by solid lines are measured using \( \Delta \eta \) gap of 1.0 in \( v_2(2) \). Dashed lines represent the results using \( v_{2,c} \) with \( \eta \) gaps of 0, 0.5 and 1.4.](image)
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