Chiral Magnetic Effect Search in p(d)+Au, Au+Au Collisions at RHIC

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The chiral magnetic effect (CME) refers to charge separation along a strong magnetic field of single-handed quarks, caused by interactions with topological gluon fields from QCD vacuum fluctuations. A major background of CME measurements in heavy-ion collisions comes from resonance decays coupled with elliptical flow anisotropy. These proceedings present two new studies from STAR to shed further light on the background issue: (1) small system p+Au and d+Au collisions where the CME signal is not expected, and (2) pair invariant mass dependence where resonance peaks can be identified.

Keywords: CME; QCD; RHIC.

1. Introduction

Quark interactions with topological gluon fields can induce chirality imbalance and local parity violation in quantum chromodynamics (QCD)^{1,2}. In relativistic heavy-ion collisions, this can lead to observable electric charge separation along the strong magnetic field, $\vec{B}$, produced by spectator protons³. This is called the chiral magnetic effect (CME). The commonly used observable to search for the CME-induced charge separation is the three-point correlator difference⁴, $\Delta\gamma \equiv \gamma_{OS} - \gamma_{SS}$; $\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle \approx \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_2$, where ϕ_α and ϕ_β are the azimuthal angles of two charged particles, of opposite electric charge sign (OS) or same sign (SS), and ψ_{RP} is that of the reaction plane (span by the impact parameter direction and the beam) to which $\vec{B}$ is perpendicular on average. The latter is often surrogated by the azimuthal angle of a third particle, ϕ_c , with a resolution correction factor given by the particle's elliptic anisotropy (v_2). Significant $\Delta\gamma$ has indeed been observed in heavy-ion collisions⁵. One of the difficulties in its CME interpretation is a major background contribution arising from the coupling of resonance decay correlations and the v_2 stemming from the participant geometry^{6,7,8,9,10}.

In non-central heavy-ion collisions, the participant plane azimuthal angle (ψ_{PP}), although fluctuating¹¹, is generally aligned with the ψ_{RP} . The $\Delta\gamma$ measurement is

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thus *entangled* by the CME and background contributions. In small-system p(d)+A collisions, however, the ψ_{PP} is determined purely by geometry fluctuations, uncorrelated to the impact parameter or the $\vec{B}$ direction^{12,13}. As a result any CME would average to zero $\Delta\gamma$ in those collisions. Background sources, on the other hand, contribute similarly to small-system p(d)+A and heavy-ion collisions when measured with respect to the event plane (EP) reconstructed from mid-rapidity particles (as a proxy for the ψ_{PP}). Due to the fluctuating nature of the small systems p(d)+A, the EPs reconstructed over a large pseudorapidity (η) gap can be uncorrelated, and therefore measurements with respect to a forward EP are sensitive neither to CME nor to the background. Recent CMS data at the LHC show that the $\Delta\gamma$ from p+Pb is comparable to that from Pb+Pb collisions at similar multiplicities^{12,14}, indicating dominant background contribution to the latter. In this report, we present results from similar control experiments using p+Au and d+Au collisions at RHIC.

Because the main backgrounds come from resonance decays, we devise a new analysis approach exploiting the particle pair invariant mass, m_{inv} , to identify the backgrounds and hence to extract the possible CME signal. The $\Delta\gamma$ signal is reported at large m_{inv} where resonance background contributions are small. A two-component model fit to the low mass region is also reported.

The results reported here use particles in the full TPC acceptance ($|\eta| < 1$) for all three particles, with transverse momentum $0.2 < p_T < 2.0$ GeV/c, and for identified $\pi^\pm$ with $0.2 < p_T < 1.8$ GeV/c. No η gap ($\Delta\eta$) is applied between any pair among the three particles for calculating $\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle$. The v_2 used for the resolution correction should, ideally, be free of non-flow. We obtain v_2 by the two-particle cumulant, applying a cut of $\Delta\eta > 1.0$ to reduce non-flow contaminations.

2. Results from small systems

Figure 1(Left) shows the γ_{SS} and γ_{OS} results as functions of particle multiplicity, N , in p+Au and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Here N is taken as the geometric mean of the multiplicities of particle α and β . The systematic uncertainties on γ are estimated by varying the track quality cuts, the correction method used for the detector azimuthal non-uniformity, and the p_T range of the particle c . For comparison the corresponding Au+Au results are also shown. The trends of the correlator magnitudes are similar, decreasing with N . Similar to LHC, the small system p(d)+Au data at RHIC are found to be comparable to Au+Au results at similar multiplicities.

Since the p(d)+Au data are all backgrounds, the $\Delta\gamma$ should be approximately proportional to the v_2 of the background sources, in turn the v_2 of final-state particles. It should also be proportional to the number of background sources, and, because $\Delta\gamma$ is a pair-wise average, inversely proportional to the total number of pairs. As the number of background sources likely scales with N , we have $\Delta\gamma \propto v_2/N$. Therefore, to gain more insight, we study the scaled correlator,

Fig. 1. (Color online) The γ_{SS} , γ_{OS} (Left panel) and $\Delta\gamma$ (Right panel) correlators in p+Au and d+Au collisions as a function of multiplicity, compared to those in Au+Au collisions. Particles α , β and c are from the TPC pseudorapidity coverage of $|\eta| < 1$ with no η gap applied. The $v_{2,c}\{2\}$ is obtained by two-particle cumulant with η gap of $\Delta\eta > 1.0$. Statistical uncertainties are shown by the vertical bars and systematic uncertainties are shown by the caps.

$\Delta\gamma_{\text{scaled}} = \Delta\gamma \times N/v_2\{2\}$. The $v_2\{2\}$ with a η gap of 1.0 is shown as a function of N in p+Au, d+Au, and Au+Au collisions in Fig. 2(Left). Figure 2(Right) shows the $\Delta\gamma_{\text{scaled}}$ as a function of N in p(d)+Au collisions, and compares to that in Au+Au collisions. AMPT simulation results for d+Au and Au+Au are also plotted for comparison, which can account for about 2/3 of the STAR data and are approximately constant over N . The $\Delta\gamma_{\text{scaled}}$ in p(d)+Au collisions are compatible or even larger than that in Au+Au collisions. Since in p(d)+Au collisions only the background is present, the data suggest that the peripheral Au+Au measurement may be largely, if not all, background. For both small-system p(d)+Au and heavy-ion collisions, the $\Delta\gamma_{\text{scaled}}$ is approximately constant over N . Given that the background is large suggested by the p(d)+Au data, the approximate N -independent $\Delta\gamma_{\text{scaled}}$ in Au+Au collisions is consistent with the background scenario.

Fig. 2. (Color online) (Left panel) The measured two-particle cumulant v_2 of charged particles ($0.2 < p_T < 2.0$ GeV/c) with η gap of 1.0, and (Right panel) the scaled three-point correlator difference in p+Au and d+Au collisions as functions of N , compared to those in Au+Au collisions. AMPT simulation results for d+Au and Au+Au are also plotted for comparison.

Fig. 3. The inclusive $\Delta\gamma$ over all mass (black) and at $m_{inv} > 1.5 \text{ GeV}/c^2$ (green) as a function of centrality in Au+Au collisions at 200 GeV.

In terms of CME, on the other hand, the number of local topological domains, N_{domain} , is likely proportional to the collision volume, so $N_{\text{domain}} \propto N$. Since the topological charge randomly fluctuates, the charge asymmetry $a_1 \propto \sqrt{N_{\text{domain}}}/N$. As a result, the $\Delta\gamma \propto a_1^2$ would be inversely proportional to N , similar to the background scenario. The CME-induced charge separation is expected to be proportional to $\langle B^2 \cos 2(\psi_B - \psi_2) \rangle^5$, where ψ_B is the azimuthal direction of $\vec{B}$. The quantity may have a similar N -dependence as the v_2 's but the present theoretical uncertainties are large^{15,16}. Thus, the N -dependence of the CME and the background may, unfortunately, be similar. Given the present uncertainties, a small finite CME signal is not disallowed in the measured $\Delta\gamma$ in heavy-ion collisions. The present analysis does not currently allow conclusive statements to be made regarding the presence of CME.

3. Results from the invariant mass method

As aforementioned, the major background arises from resonance decay correlations coupled with v_2 . With increasing mass, the data show that resonance contributions to the difference between OS and SS pairs decrease. It is therefore possible to exclude them “entirely” by applying a lower cut on m_{inv} . Figure 3 shows the $\Delta\gamma$ results with and without applying a cut of $m_{inv} > 1.5 \text{ GeV}/c^2$. The results are summarized in Table 1. With the m_{inv} cut, the $\Delta\gamma$ is significantly reduced from the inclusive measurement, and is consistent with zero within the current uncertainty.

Table 1. The inclusive $\Delta\gamma$ over all mass and $\Delta\gamma$ at $m_{inv} > 1.5 \text{ GeV}/c^2$ for different centralities in Au+Au collisions at 200 GeV.

Centrality	$\Delta\gamma$ in all mass (A)	$\Delta\gamma$ at $m_{inv} > 1.5 \text{ GeV}/c^2$ (B)	B/A
50-80%	$(7.45 \pm 0.21) \times 10^{-4}$	$(1.3 \pm 5.7) \times 10^{-5}$	$(1.8 \pm 7.6)\%$
20-50%	$(1.82 \pm 0.03) \times 10^{-4}$	$(7.7 \pm 9.0) \times 10^{-6}$	$(4.3 \pm 4.9)\%$
0-20%	$(3.70 \pm 0.67) \times 10^{-5}$	$(-0.1 \pm 1.8) \times 10^{-5}$	$(-3.8 \pm 49)\%$

The CME is expected to be a low p_T phenomenon¹⁷; its contribution to high mass may be small. In order to extract CME at low mass, resonance contributions

Fig. 4. (Color online) Pair invariant mass (m_{inv}) dependence of the relative excess of OS over SS charged π pairs, $r = (N_{OS} - N_{SS})/N_{OS}$ (top panel), three-point correlator difference, $\Delta\gamma = \gamma_{OS} - \gamma_{SS}$ (middle panel), and the ratio of $\Delta\gamma/r$ (bottom panel) in 20-50% Au+Au collisions at 200 GeV. Errors shown are statistical. The red curve in the middle panel shows the two-component model fit assuming a constant CME contribution independent of m_{inv} ; The blue curve in the bottom panel shows the corresponding resonance response function, $R(m_{inv})$.

need to be subtracted. To this end, we show in Fig. 4(a) the relative OS and SS pair abundance difference, $r = (N_{OS} - N_{SS})/N_{OS}$, and in Fig. 4(b) the $\Delta\gamma$ correlator as a function of m_{inv} in mid-central (20-50%) Au+Au collisions at 200 GeV. The data show resonance structures in r and $\Delta\gamma$ as functions of m_{inv} : a clear peak from K_s^0 decay is observed, and possible ρ and f^0 peaks are visible. The $\Delta\gamma$ correlator traces the distributions of those resonances.

The $\Delta\gamma$ in Fig. 4(b) may be composed of two components, a resonance decay background and a CME signal: $\Delta\gamma = r(m_{inv}) \times R(m_{inv}) + \text{CME}(m_{inv})$. The background depends on $r(m_{inv})$, with a smooth response function $R(m_{inv})$, and is therefore peaky in m_{inv} . We assume that the CME component is smooth in m_{inv} . If the CME contribution was appreciable, then the ratio of $\Delta\gamma/r$ shown in Fig. 4(c) would reveal a structure resembling the inverse shape of r ¹⁸. However, a more or less smooth dependence is observed; suggesting insignificant CME signal contributions.

In order to isolate the possible CME from the resonance contributions, the two-component model is used to fit the $\Delta\gamma$ as a function of m_{inv} . We use the first-order polynomial function for $R(m_{inv})$, motivated by the data in Fig. 4(c) and MC simulation¹⁸. At present, no theoretical calculation is available on the m_{inv} dependence of the CME, therefore we consider a constant CME distribution independent of m_{inv} (Fig. 4(b)). Future theoretical calculations of the CME mass dependence would be valuable.

4. Summary

The chiral magnetic effect (CME) can produce charge separation perpendicular to the reaction plane. Charge separation measurements by the three-point correlator ($\Delta\gamma$) are contaminated by major backgrounds arising from resonance decay

correlations coupled with the elliptical anisotropy (v_2). To further shed light on the background and to reduce/eliminate background contamination, we have studied the small-system p(d)+Au collisions in comparison to Au+Au collisions, and the $\Delta\gamma$ correlator as a function of the particle pair invariant mass (m_{inv}).

With respect to the second-order event plane, the p+Au and d+Au charge dependent correlations are backgrounds. Peripheral Au+Au data are similar to those of p+Au and d+Au. The scaled correlator ($\Delta\gamma \times N/v_2$) from peripheral to mid-central Au+Au collisions is approximately constant over multiplicity. Similar dependence is found in AMPT. These data indicate a dominant contribution from background to the peripheral and mid-central heavy-ion collisions, and do not show clear evidence for the presence of the CME in those collisions.

A new method exploiting m_{inv} is used to identify resonance backgrounds and the possible CME. In order to exclude the resonance contributions, we apply a lower cut on m_{inv} . At high mass ($m_{inv} > 1.5 \text{ GeV}/c^2$), $\Delta\gamma$ is consistent with zero within uncertainty. In the low mass region ($m_{inv} < 1.5 \text{ GeV}/c^2$), data show resonance structures in $\Delta\gamma$ as function of m_{inv} . A two-component fit is devised where the background is peaky following the resonance contributions and the CME signal is assumed to be smooth in m_{inv} . A constant distribution for the latter have been studied; theoretical guidance on its mass dependence would be valuable to further our understanding.

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