Systematic Searches for the Chiral Magnetic Effect and the Chiral Vortical Effect Using Identified Particles at RHIC/STAR

Liwen Wen(for the STAR Collaboration)
University of California, Los Angeles, California, USA
E-mail: lwen@physics.ucla.edu

Abstract. STAR measurements of identified-particle correlations in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV are used to explore possible hierarchical structures in the particle-dependent correlations due to the chiral magnetic effect (CME) and the chiral vortical effect (CVE). Correlations of p-π (p-Λ), sensitive to the possible CME (CVE), are reported and compared with hadron-hadron (h-h) correlation, yielding a charge separation ordering (p-$\Lambda > p$-$\pi \sim$ h-h). The estimated background strength from transverse momentum conservation (TMC) hardly shows any centrality dependence. For Au+Au collisions at 19.6, 39 and 200 GeV, clear signals above the background are observed for mid-central and peripheral collisions while results from central collisions ($< 15\%$) can not separate from the background. For the results from collisions at 7.7 GeV, all are consistent with the TMC background although the errors are large.

1. Introduction

Chirality imbalance in a quark-gluon plasma could occur on an event-by-event basis. In the presence of a strong magnetic field (vorticity) produced in noncentral heavy-ion collisions, the chirality imbalance may lead to novel non-dissipative transport phenomena, among which are the CME and the CVE [1]. As the experimental manifestation of the CME, the signals of electric charge separation across the reaction plane have been extensively searched for using charged-hadron correlations at the Relativistic Heavy Ion Collider (RHIC) [2] and the Large Hadron Collider (LHC) [3]. Similarly, baryonic charge separation is considered to be the evidence for the CVE. However, theoretical predictions on the magnitude of the CME (CVE) and the particle-type dependence are still limited. In addition, previous charged-hadron correlations may contain the CVE (because protons are baryons but not eliminated), so experimental efforts to study these two effects respectively become of great importance. Identified-particle correlations can probe a specific underlying mechanism for the electric (baryonic) charge separation. In this article, we report γ correlations of p-Λ and p-π for Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV at STAR/RHIC. The results are compared with h-h correlations. Although the γ correlator has scaled down flow-related background by approximately a factor of elliptic flow (v_2) [1], the background contribution cannot be completely ignored. In Sec. 4, we present our recent estimation of one flow-related background source, transverse momentum conservation (TMC), and rearrange our published BES results [4] to study the background effects.

2. Data analysis

Around 200 million minimum-bias events of Au+Au collisions at $\sqrt{s_{\rm NN}}$ =200 GeV from RHIC Run11 have been used in this analysis. With the Time Projection Chamber (TPC), the deviation of specific energy loss rate (dE/dx) from the expected value is used to identify electrons, pions, kaons and protons. The Time-of-Flight (TOF) detector provides the mass information to further select particles of interest. A pseudorapidity cut of $|\eta| < 1$ is applied to all the measured particles. Standard topological cuts are used to reconstruct Λ via $\Lambda \to \pi^- + p$ ($B.R. = 63.9 \pm 0.5\%$ [5]). Protons with $0.4 < p_T < 2.0$ GeV/c, Λ's with $0.5 < p_T < 5.0$ GeV/c and other hadrons with $0.15 < p_T < 2.0$ GeV/c are used in the corresponding correlation measurements. The second-order event plane, constructed from TPC tracks, is used to approximate the real reaction plane. The final event plane orientation is corrected for the event plane resolution, and the shifting method is used to eliminate detector effects.

The three-point correlator γ, sensitive to charge separation fluctuations, is used to search for the chiral effects [6]:

$$\gamma \equiv \langle \phi_\alpha + \phi_\beta - 2\Psi_{\rm RP} \rangle, \tag{1}$$

where $\phi_{\alpha,\beta}$ refers to the azimuthal angle of the correlated particles, and $\Psi_{\rm RP}$ denotes the reaction plane orientation.

3. Gamma correlation results

Assuming s quarks take part in chiral dynamics the same way as u, d quarks do, p-Λ correlations are proposed to search for the CVE with limited contamination from the electric charge separation signal, because of the electric neutrality of Λ. Figures 1 and 2 show opposite- and same-sign correlations of p-Λ (left plot), as well as their difference (right plot) in Au+Au collisions at 200 GeV. Significant separation signals are observed in mid-central to peripheral collisions, which qualitatively meets the theoretical expectation for the CVE [1]. As a systematic check of h-h correlations, p-π correlations (Figs. 3 and 4) in 200 GeV Au+Au show that the electric charge separation signals have the magnitudes close to h-h correlations, which suggests a similar underlying mechanism (CME) as expected.

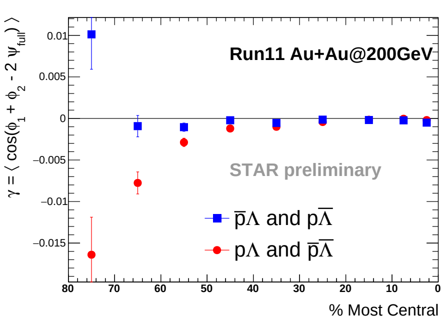


Figure 1. Opposite- and same-sign γ correlations of p-Λ pairs for Au+Au collisions at 200 GeV.

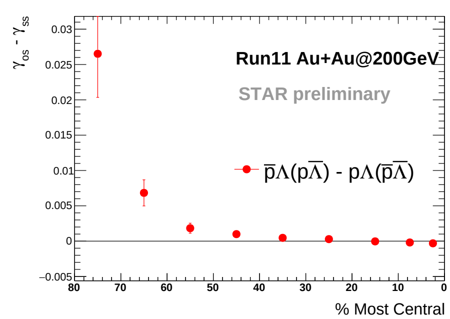
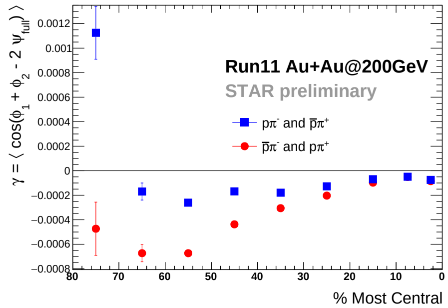


Figure 2. Difference between opposite- and same-sign γ correlations of p-Λ for Au+Au collisions at 200 GeV.

Figure 5 shows several identified-particle correlations under study, and exhibits a hierarchical structure of possible chiral effects. The large difference between baryonic and electric charge separation may suggest two differently driven mechanisms (magnetic field and vorticity), but more investigations are needed to reveal a true relationship between these two types of correlations. In Fig. 6, N_{part}, number of participants, scaled results are plotted to effectively eliminate the dilution effect, and show that in most central collisions, the signals are consistent with zero.



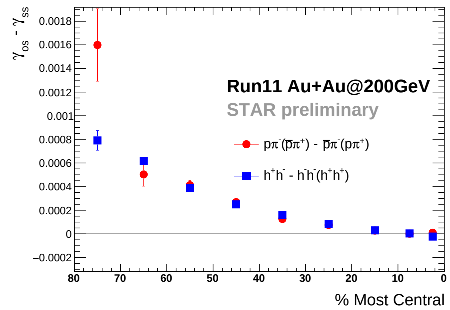
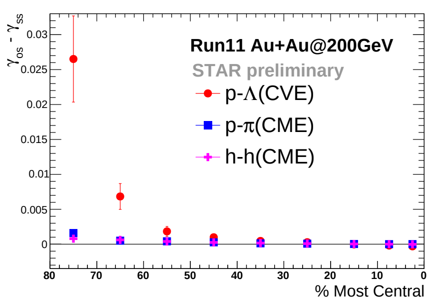


Figure 3. Opposite- and same-sign γ correlations of p-π pairs for Au+Au collisions at 200 GeV.

Figure 4. Difference between opposite- and same-sign γ correlations of p-π for Au+Au collisions at 200 GeV, compared to the h-h result.



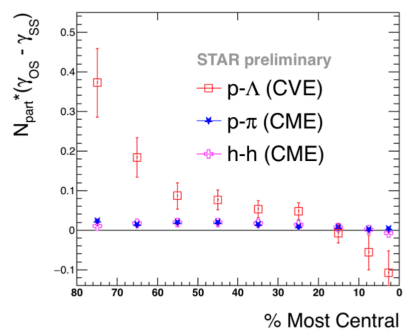
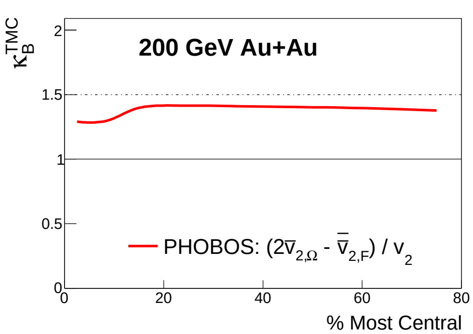


Figure 5. Comparison of $\gamma_{os} - \gamma_{ss}$ between p-Λ, p-π, h-h pairs for Au+Au collisions at 200 GeV.

Figure 6. $N_{\rm part}$ scaled $\gamma_{os} - \gamma_{ss}$ of p-Λ, p-π, h-h for Au+Au collisions at 200 GeV.

4. Flow background estimation



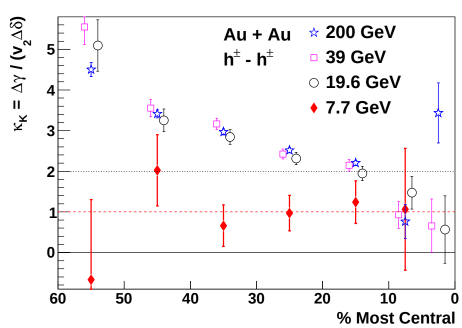


Figure 7. Estimated $\kappa_{\rm B}^{\rm TMC}$ as a function of centrality for Au+Au collisions at 200 GeV.

Figure 8. Centrality dependence of $\kappa_{\rm K}$ for Au+Au collisions at different energies (7.7, 19.6, 39 and 200 GeV).

The flow-related background is significantly suppressed in the construction of the γ correlator [1], but its effect on existing measurements is still non-negligible. Disentanglement of the background and the CME/CVE signal has been the recent focal point of theoretical and experimental efforts. In Ref. [7], a modified correlator, $H = (\kappa_{\rm B} v_2 \delta - \gamma)/(1 + \kappa_{\rm B} v_2)$, is proposed to remove the flow-induced background in an empirical approach. Here $\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$, represents the two-particle correlation that includes contributions from TMC, local charge conservation (LCC), flowing resonances and so on. The coefficient, $\kappa_{\rm B}$, quantifies the background strength, and requires a practical approach to gauge its range in our correlation measurements.

Theoretically, the TMC effect on the γ correlator can be formulated and the corresponding $\kappa_{\rm B}^{\rm TMC}$ is approximated by $\kappa_{\rm B}^{\rm TMC} \approx 2 - \bar{v}_{2,F}/\bar{\bar{v}}_{2,\Omega}$ [7]. The $\bar{v}_{2,F}$ and $\bar{\bar{v}}_{2,\Omega}$ denote the p_T-weighted and p_T^2-weighted v_2 of particles of interest in the full space and the detector acceptance, respectively. The PHOBOS Collaboration at RHIC provides a v_2 measurement for charged particles over a broad phase space coverage in pseudo-rapidity [8]. Combined with transverse momentum spectrum information, $\kappa_{\rm B}^{\rm TMC}$ as a function of centrality is estimated and shown in Fig. 7. The magnitude is almost constant across different centralities and slightly smaller than 1.4. We can use this result as a reference to check our previous *h*-*h* correlations.

We define a "normalized" signal+background, $\kappa_{\rm K}$:

$$\kappa_{\rm K} = \Delta\gamma/(v_2 \Delta\delta), \tag{2}$$

which denotes the minimum $\kappa_{\rm B}$ value needed to saturate the gamma correlator strength with the background. Any result that is larger than real κ_B might represent the genuine physics. In Fig. 8, the *h*-*h* correlations in BES I [4] show that except for the 7.7 GeV data, $\kappa_{\rm K}$ for higher energies in mid-central collisions is always above the empirically allowed range of $\kappa_{\rm B}$ (between 1 and 2), where the $\kappa_{\rm B}$ is only constructed from TMC as a test case. This means that our measured H correlation strength cannot be entirely caused by the flow-induced background: the signal+background is larger than the background in the "κ" unit. There must be additional contributions which may be related to the CME. On the other hand, $\kappa_{\rm K}$ in Au+Au collisions at 7.7 GeV is consistent with unity, indicating a different behavior than that in collisions at higher energies.

5. Summary and outlook

γ correlations of p-Λ and p-π have been presented and compared with hadron-hadron(*h*-*h*) correlations in Au+Au collisions at 200 GeV. The p-π correlations show similar signal magnitudes as *h*-*h*, while the p-Λ correlations have much larger signals in mid-central to peripheral collisions. The $\kappa_{\rm B}^{\rm TMC}$ value has been estimated. Except for the 7.7 GeV data, the CME observables for higher energies are identified to be above the empirical background. In the future, isobaric collisions may provide a good control on the flow dependent background. Since the flow background will be the same in ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr and ${}^{96}_{44}$Ru+${}^{96}_{44}$Ru collisions, a potential difference of particle correlation between these two colliding systems will allow us to relate the correlation measurements with the strength of the magnetic field, which is an essential step toward the discovery of the CME [9].

References

[1] Kharzeev D E *et al.* 2016 *Prog. Part. Nucl. Phys.* **88**, 1
[2] Abelev B I *et al.* (STAR Collaboration) 2009 *Phys. Rev. Lett.* **103** 251601; 2010 *Phys. Rev. C* **81** 054908
[3] Adam J *et al.* (ALICE Collaboration) 2014 *Phys. Rev. C* **93** 044903
[4] Adamczyk L *et al.* (STAR Collaboration) 2014 *Phys. Rev. Lett.* **113** 052302
[5] Olive K A *et al.* (Particle Data Group) 2014 *Chin. Phys. C* **38** 090001 and 2015 update.
[6] Voloshin S A 2004 *Phys. Rev. C* **70** 057901
[7] Bzdak A, Koch V and Liao J 2011 *Phys. Rev. C* **83** 014905
[8] Alver B *et al.* 2005 *Phys. Rev. C* **83** 024913; *Phys. Rev. C* **72** 014904
[9] Deng W-T, Huang X-G, Ma G-L and Wang G 2016 arXiv:1607.04697