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Towards Measurements of Chiral Effects Using Identified Particles from STAR

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Abstract

We report recent STAR results on searching for the Chiral Magnetic Effect via measurements of γ correlation and κ_K parameter for charged hadrons and identified particle pairs ($\pi\pi$, pK, πK, pp, $p\pi$) in Au+Au collisions at 200 GeV. We compare the κ_K parameters with expectations from the AMPT simulations. Sizable γ correlations for charged hadrons, using Time Projection Chamber event plane, in p+Au and d+Au 200 GeV have been observed, and the correlations in these small systems are reduced to near zero when the event planes from forward detectors are used. We will also present our results on the Chiral Magnetic Wave searches from p+Au collisions at 200 GeV.

Keywords:
Chiral Magnetic Effect, Chiral Magnetic Wave, γ correlation, κ_K parameter

1. Introduction

Quark chirality imbalance and a strong magnetic field can both be present in heavy-ion collisions and the coupling of these can result in the Chiral Magnetic Effect (CME) [1]. Theoretical calculations also predict possible formation of the Chiral Magnetic Wave (CMW) [2]. Searches for chirality effects based on event-by-event analyses have been a subject for intensive theoretical and experimental investigations [3]. We use a three-point correlator γ (see Sec. 2) to measure the fluctuations in the charge separation magnitudes and use subtraction of Opposite-Sign (OS) and Same-Sign (SS) charged particle pairs to suppress common backgrounds. Recent studies have indicated that a considerable amount of residual background remains in the subtracted γ correlator [4, 5]. To quantify the range of the residual background, we use the κ_K parameter (see Sec. 2) to compare with the expected range of known background levels from AMPT simulations(v2.21, string melting, hadronic scattering turned on, charge not strictly conserved [6]).

We present recent STAR results on searches for chirality effects at RHIC. In Sec. 3.1, we show correlation measurements for charged hadrons and identified particles (π, K, p) from Au+Au collisions. In Sec. 3.2 and Sec. 3.3 we discuss results from small systems such as p+Au and d+Au collisions where there is no measurable CME or CMW signal expected due to the de-correlation between magnetic field direction and the reaction plane.

[1]A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.

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2. Observables and Data Analysis

The three-point γ correlator [7] is defined as follows,

$$\gamma = \langle \cos(\phi_a + \phi_b - 2\Psi_2) \rangle \text{ or } \langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle / v_{2,c}, \tag{1}$$

which is sensitive to charge separation across the reaction plane in heavy-ion collisions. The ϕ_a and ϕ_b are the azimuthal angles of a correlated particle pair, and Ψ_2 and ϕ_c are used to represent the second-order event plane. $v_{2,c}$ is the v_2 of the third particle c. A finite $\gamma_{OS} - \gamma_{SS}$, which quantifies the event-by-event fluctuation of charge distribution asymmetry, will indicate a possible charge separation across the reaction plane. Here "OS" denotes the particle pair with opposite charge sign and "SS" the same charge sign. For convenience, the notation $\Delta\gamma$ and $\gamma_{OS} - \gamma_{SS}$ will be used interchangeably in the rest of the proceedings.

The flow-related background is known to contribute to the γ correlation. To quantitatively estimate the flow background, a background model for γ and the two-particle correlator $\delta \equiv \langle \cos(\phi_a - \phi_b) \rangle$ has been proposed and a H correlator has been introduced [8]:

$$\Delta\delta \equiv \langle \cos(\phi_a - \phi_b) \rangle_{OS-SS} = \Delta F + \Delta H \tag{2}$$

$$\Delta\gamma \equiv \langle \cos(\phi_a + \phi_b - 2\Psi_2) \rangle_{OS-SS} = \kappa v_2 \Delta F - \Delta H, \tag{3}$$

where H is the charge separation due to the CME. "Δ" refers to difference between "OS" and "SS" correlations. κ quantifies the coupling between v_2 and δ, which contaminates the γ measurements:

$$\kappa = \frac{\Delta\gamma + \Delta H}{v_2(\Delta\delta - \Delta H)}. \tag{4}$$

We introduce the κ_K parameter by seting ΔH to be zero for a maximum background scenario $\kappa_K \equiv \kappa|_{\Delta H=0} = \frac{\Delta\gamma}{v_2\Delta\delta}$. The κ_K parameter can be compared with κ from background models such as AMPT simulations. Any excess of measured κ_K for particle pairs of interest over the expected range from background models could indicate the presence of physics beyond known background, *e.g.* the CME.

To search for the CMW in heavy-ion collisions, we study the charge asymmetry dependence of the difference between π^- and π^+ elliptic flow [9]: $v_2(\pi^\pm) = v_2^{base}(\pi^\pm) \mp rA_{ch}/2$, where $v_2^{base}(\pi^\pm)$ is the baseline elliptic flow that is not related to the CMW, $A_{ch} = (N_+ - N_-)/(N_+ + N_-)$ is the charge asymmetry of the events and r is the slope reflecting the strength of the CMW.

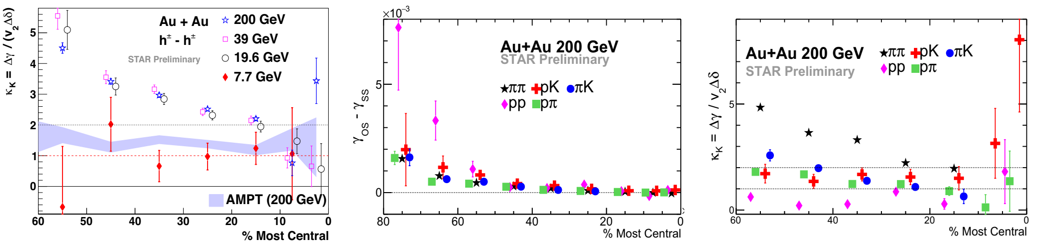
For identified particle correlation measurements, ~200M minimum-bias (MB) events of Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV from RHIC Run11 were used. Tracks reconstructed in the Time-Projection Chamber (TPC) with transverse momentum p_T from 0.15 to 2.0 GeV/c were used for the estimation of the second-order event plane. Particle species (π, K, p) were identified by applying cuts on the energy loss (dE/dx) in the TPC. Moreover, the particle velocity β measured via the Time-Of-Flight (TOF) detector helps further to select the desired particles. In small-system measurements, the Beam-Beam Counter (BBC, $3.8 < |\eta| < 5.2$) [10] and the Zero Degree Calorimeter (ZDC, $6 < |\eta|$) [11] were also used for forward event-plane reconstruction. The data selected by High-Tower trigger (HT, triggered on the energy deposition in the EM calorimeter) in p+Au collisions were analyzed as well.

3. Results

3.1. Search for Chiral Magnetic Effect in Au+Au at RHIC

Figure 1a shows the κ_K measurements for charged hadrons in Au+Au 7.7, 19.6, 39, and 200 GeV [4]. The AMPT result for Au+Au collisions at 200 GeV serves as a background reference without the CME and shows a weak centrality dependence between 1 and 2. STAR data for energies from 19.6 to 200 GeV show very similar magnitudes of κ_K, well above the AMPT estimation of background levels in mid-peripheral and mid-central collisions. Results at 7.7 GeV fall into the background range, suggesting the turn-off of the CME in collisions at this low energy. STAR data [12] showed that in peripheral collisions an additional short or intermediate-range background correlation also contributes to the γ, which may finally lead to the rise in κ_K in peripheral collisions.

Figure 1b shows $\Delta\gamma$ for identified particle pairs ($\pi\pi$, pK, πK, pp, $p\pi$) from peripheral to central collisions. The pp correlation magnitude is significantly larger than the other pairs. However, κ_K (see Figure 1c) for these particle pairs indicates very different behavior. Only $\pi\pi$ correlation has κ_K values larger than AMPT-expected background level (∼1-2) in mid-peripheral and mid-central collisions, while the other pairs are falling within the range of 1 to 2 except pp pairs. κ_K for pp is found to be lower than 1 in those centrality bins. These results seem to suggest that the major contribution to the $h^\pm h^\pm$ charge separation signal arises from $\pi\pi$. The other particle pairs cannot be distinguished from background scenario and will require more simulation statistics (the current statistics are limited by speed of AMPT simulations) to determine the background. The charge separation and background level for pp pairs will require further investigations.



(a) (b) (c)

Fig. 1: (Color online) (a) $\gamma_{\rm OS} - \gamma_{\rm SS}$ for $h^\pm h^\pm$ in Au+Au collisions at 7.7, 19.6, 39, 200 GeV, and AMPT Au+Au 200 GeV simulations. (b) $\gamma_{\rm OS-SS}$ and (c) κ_K for $\pi\pi$, pK, πK, pp, and $p\pi$ as a function of centrality in Au+Au collisions at 200 GeV.

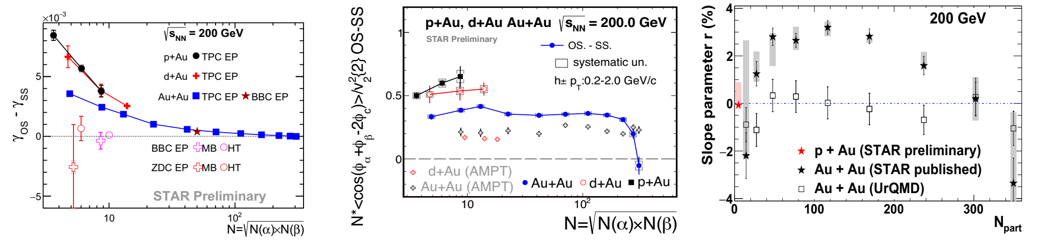
3.2. Study of correlators from p+Au and d+Au collisions

Since small systems are believed to be dominated by background, the measurements of correlators from those systems can shed more light on our understanding of Au+Au results [13]. Figure 2a shows $\Delta\gamma$ between "OS" and "SS" correlations for charged hadons in p+Au, d+Au collisions at 200 GeV, in comparison to data from Au+Au 200 GeV. Using event plane reconstructed from the TPC, the p+Au and d+Au data exhibit larger values of $\Delta\gamma$ than Au+Au collisions. However, when using the forward event plane (reconstructed from BBC and ZDC), $\Delta\gamma$ in p+Au 200 GeV is consistent with zero within error bars. On the other hand, in 50-60% Au+Au collisions at 200 GeV, $\Delta\gamma$ measured with the BBC event plane (red star) is consistent with that obtained with the TPC event plane. The p+Au and d+Au $\Delta\gamma$ measurements with the TPC event plane are presumably all non-CME background, arising from intrinsic particle correlations (non-flow) coupled with the anisotropy of those particles. The measurements with forward event planes greatly suppress nonflow contributions, leading to the vanishing $\Delta\gamma$.

In a pure flow-induced background scenario, $\Delta\gamma$ scaled by multiplicity and v_2 should be constant across centrality bins. Figure 2b [14] shows the scaled $\Delta\gamma$ from p+Au, d+Au, and Au+Au collisions. The scaled $\Delta\gamma$ from p+Au and d+Au (background) is higher than the data from Au+Au, demanding better understanding of our background sources. The AMPT simulation (background) cannot fully describe the STAR data from d+Au and Au+Au collisions at 200 GeV. The AMPT background data can only account for 2/3 of the STAR measured correlator strength from peripheral to mid-central collisions and miss STAR data trend for the most central collisions completely.

3.3. Search for Chiral Magnetic Wave in p+Au collisions at RHIC

In the absence of correlations between the magnetic field and the reaction plane, the CMW measurements in p+Au collisions can serve as a background reference for Au+Au results. Figure 2c shows STAR measurement of the r slope parameter from p+Au collisions in comparison with data from Au+Au 200 GeV



(a) (b) (c)

Fig. 2: (Color online) (a) κ_K for charged hadrons in p+Au, d+Au, and Au+Au collisions using TPC/BBC/ZDC event planes and Mini-Bias (MB)/High-Tower (HT) triggers (p+Au) as a function of multiplicity (N(α) and N(β) are the correlated particle multiplicities). (b) Scaled three-point correlation for charged hadrons in p+Au, d+Au, and Au+Au collisions at 200 GeV, as well as AMPT simulations for p+Au and d+Au, as a function of multiplicity. (c) r of $\Delta v_2(A_{ch})$ between π^- and π^+ as a function of number of participants in p+Au, Au+Au and Au+Au (UrQMD) 200 GeV collisions.

and UrQMD model (v2.3) [15]. The measured r in p+Au collisions is consistent with zero, which is similar to the result from peripheral Au+Au collisions, indicating there is no evidence for the CMW in p+Au collisions at 200 GeV.

4. Summary

We have reported STAR measurements of γ correlation and κ_K parameters for identified particle pairs ($\pi\pi$, pK, πK, pp, $p\pi$) in Au+Au collisions at 200 GeV. Only for $\pi\pi$ correlations, the κ_K parameter has a similar magnitude to charged hadrons in Au+Au collisions at 200 GeV, which is larger than estimated background from AMPT. κ_K values for other pairs, pK, πK, $p\pi$ are within expected range at the model-estimated background level. The pp correlations yield a κ_K smaller than estimated background level. Measurements of $\Delta\gamma$ for charged hadrons in p+Au and d+Au 200 GeV show sizable magnitudes using TPC event plane. The $\Delta\gamma$ signal is significantly reduced when a large η gap is introduced between particles of interest and those used for the event plane reconstruction. The slope of $\Delta v_2(A_{\rm ch})$ for charged pions, denoted as r, has also been measured and is consistent with the absence of the CMW in p+Au collisions.

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