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Search for the Chiral Magnetic Wave with Anisotropic Flow of Identified Particles at RHIC-STAR

Qi-Ye Shou (for the STAR Collaboration)

Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

Abstract

The chiral magnetic wave (CMW) has been theorized to propagate in the Quark-Gluon Plasma formed in high-energy heavy-ion collisions. It could cause a finite electric quadrupole moment of the collision system, and may be observed as a dependence of elliptic flow, v_2, on the asymmetry between positively and negatively charged hadrons, $A_{\rm ch}$. However, non-CMW mechanisms, such as local charge conservation (LCC) and hydrodynamics with isospin effect, could also contribute to the experimental observations. Here we present the STAR measurements of elliptic flow v_2 and triangular flow v_3 of charged pions, along with v_2 of charged kaons and protons, as functions of $A_{\rm ch}$ in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. The slope parameters of $\Delta v_2(A_{\rm ch})$ and $\Delta v_3(A_{\rm ch})$ are reported and compared to investigate the LCC background. The similarity between pion and kaon slopes suggests that the hydrodynamics is not the dominant mechanism. The difference between the normalized Δv_2 and Δv_3 slopes, together with the small slopes in p+Au and d+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, suggest that the CMW picture remains a viable interpretation at RHIC.

Keywords: Chiral magnetic wave, anisotropic flow, STAR experiment

1. Introduction

It is proposed that, in a chirally symmetric phase, the chiral magnetic effect (CME) and the chiral separation effect (CSE) could intertwine to form a collective excitation of the Quark-Gluon Plasma (QGP), known as the chiral magnetic wave (CMW), a long wavelength hydrodynamic mode of chirality charge densities [1, 2]. CMW is a signature of the chiral symmetry restoration, and manifests itself as a finite electric quadrupole moment of the collision system, where the "poles" ("equator") of the produced fireball acquire additional positive (negative) charge. This effect, if present, may lead to charge-dependent elliptic flow, v_2, i.e., the difference of v_2 between negatively and positively charged particles, Δv_2, could be proportional to the charge asymmetry, $A_{\rm ch}$, defined as $A_{\rm ch} = (N_+ - N_-)/(N_+ + N_-)$ with N_+ (N_-) denoting the number of positive (negative) particles in a given event.

Such charge asymmetry dependence of v_2 has been observed in Au+Au collisions in the STAR experiment [3] and in Pb+Pb collisions in the ALICE experiment [4]. However, non-CMW mechanisms could also contribute to such linear relationship between $A_{\rm ch}$ and v_2. A hydrodynamic study [5] claims that the simple transport of charges in QGP, convoluted with certain initial conditions related to isospin chemical potential, can lead to a sizable v_2 splitting of $\pi^{\pm}$. This model further predicts negative $\Delta v_2(A_{\rm ch})$ slopes for

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charged kaons and protons with larger magnitudes than the pion slopes. On the other hand, local charge conservation (LCC), together with the characteristic shape of $v_2(\eta)$ and $v_2(p_T)$, could also qualitatively explain the data [6]. In particular, it is predicted that such mechanism could give a similar effect on v_3, with the slope of $\Delta v_3(A_{\rm ch})$ being consistent with that of $\Delta v_2(A_{\rm ch})$ after normalization. In addition, in small system collisions, e.g., p+A, the magnetic field direction is presumably decoupled from the reaction plane [7], therefore the Δv_2 slopes, if observed, should be free of CMW signal and are dominated by background contributions such as LCC. These measurements have been performed by the CMS experiment [8] in p+Pb and Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV, which is consistent with the LCC picture. However, one should be aware that the magnetic field strength decays in the vacuum much faster at the LHC energies than at RHIC, and by the time of quark production, the magnetic field may become too weak to initiate the CMW [2, 9, 10]. The potential difference in the physics mechanisms between RHIC and the LHC motivates us to measure the $A_{\rm ch}$ dependence of anisotropic flow for various particle species using the STAR experiment at RHIC energy.

Here we present the results of the STAR experiment for (1) dependence of the $\Delta v_2(A_{\rm ch})$ slopes on centrality for kaons and (anti)protons in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, which tests the hydrodynamics scenario; (2) dependence of the $\Delta v_3(A_{\rm ch})$ slope on centrality for $\pi^{\pm}$ in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, which studies the contribution from LCC; (3) the $\Delta v_2(A_{\rm ch})$ slopes in p+Au, d+Au and U+U collisions, which provide more information and further helps to disentangle the CMW signal from the background.

2. Data selection and analysis method

A general overview of STAR experiment and detector can be found in [11]. For this analysis, the large-system data sample consists of minimum-bias triggered events taken by the STAR detector from 2010 to 2016, including Au+Au, p+Au and d+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, as well as U+U collisions at $\sqrt{s_{\rm NN}}$ = 193 GeV. The primary vertex of each event is required to be within 30 cm from the detector center along the beam direction, and within a radius of 2 cm from the beam along the transverse direction. All tracks are required to be within one unit around midrapidity ($|\eta| < 1$). The charged asymmetry $A_{\rm ch}$ is calculated for charged particles within transverse momentum window, $0.15 < p_T < 12$ GeV/c, excluding the low p_T (anti)protons ($p_T < 0.4$ GeV/c) which are potentially contaminated by beam-pipe knockouts. For a given centrality, events are divided into five sub-groups according to their $A_{\rm ch}$, with each subgroup having similar number of events. The true $A_{\rm ch}$ is calculated by correcting the measured $A_{\rm ch}$ for detector efficiency obtained with HIJING and GEANT Monte-Carlo simulation of the STAR detector response.

To measure the v_n, the distance of the closest approach to primary vertex of the tracks is required to be less than 1 cm to reject secondary particles, and the transverse momentum is required to be within $0.15 < p_T < 0.5$ GeV/c to guarantee good particle identification and an almost constant mean p_T as a function of $A_{\rm ch}$. Time projection chamber (TPC) and time-of-flight (TOF) detectors are jointly used to identify particle species, such as π, K and p. Most technical details of the analysis are kept to be the same as the previous STAR publication [3].

The Q-cumulant method [12] is adopted to extract the anisotropic flow. In this approach, all multiparticle cumulants are expressed with respect to flow vectors, $Q_n \equiv \sum_{k=1}^{M} e^{in\varphi_k}$. For instance, two-particle correlations for a single event and for all events, respectively, can be calculated by:

$$\langle 2' \rangle = \frac{p_n Q_n^* - m_q}{m_p M - m_q}, \qquad \langle\langle 2' \rangle\rangle = \frac{\sum_{i=1}^{N} (w_{\langle 2' \rangle})_i \langle 2' \rangle_i}{\sum_{i=1}^{N} (w_{\langle 2' \rangle})_i},$$

where p_n and Q_n^* are flow vectors and $w_{\langle 2' \rangle}$ represents the event weight. The m_p and M are the number of particles of interest (POI) and the number of reference particles (RFP), respectively, while m_q denotes the number of particles labeled by both POI and RFP. Using differential second-order cumulant, $d_n\{2\} = \langle\langle 2' \rangle\rangle$, one can estimate differential flow by $v_n\{2\} = d_n\{2\}/\sqrt{c_n\{2\}}$, where c_n represents the reference flow. An η gap of 0.3 is applied between POI and RFP to suppress short-range non-flow effects.

3. Results

3.1. *Dependence of the $\Delta v_2(A_{ch})$ slope on centrality for kaons and (anti)protons*

In addition to the aforementioned viscous hydrodynamic model with certain assumptions on isospin asymmetry, which predicts a stronger v_2 splitting in reverse order for $K^{\pm}$ than $\pi^{\pm}$ [5], kaons and protons could also behave differently than pions, owing to their larger differences in the absorption cross sections between particles and antiparticles in the hadronic stage [1]. Moreover, the Chiral Vortical Effect (CVE) [13] could also contribute to the proton slope along with the CMW. Hence, the measurements of $\Delta v_2(A_{ch})$ slopes for kaons and protons provide the direct test for all of these physics scenarios.

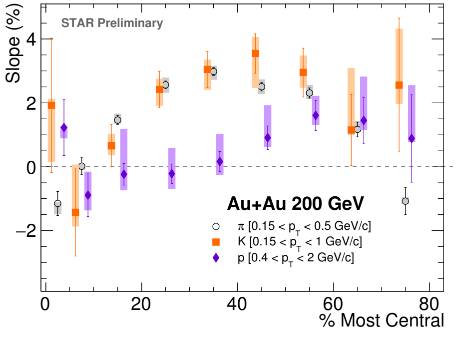

Fig. 1: Centrality dependence of the $\Delta v_2(A_{ch})$ slopes for kaons and protons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

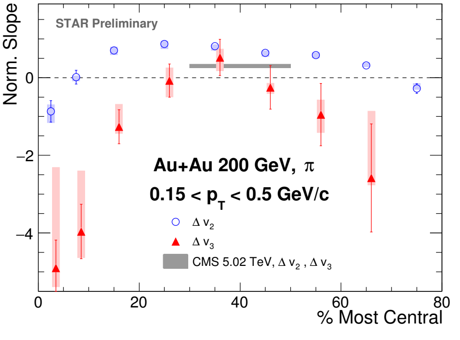

Fig. 2: The normalized $\Delta v_2(A_{ch})$ and $\Delta v_3(A_{ch})$ slopes for pions vs. centrality in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

Fig. 1 shows the centrality dependence of the kaon and proton slopes in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The kaon slope displays a rise-and-fall trend with positive values in most centralities, highly consistent with the pion slope. It neither reveals a significant absorption effect, nor suggests that the hydrodynamics with isospin asymmetry is the dominant mechanism. It is also observed that the centrality dependence of proton[1] $\Delta v_2(A_{ch})$ slopes are close to zero except for the centrality range 40 – 70%. The smaller proton slopes may suggest a mixed scenario without a dominating mechanism.

3.2. *Dependence of the $\Delta v_3(A_{ch})$ slope on centrality for $\pi^{\pm}$*

Both the LCC effect and the viscous hydrodynamics with isospin asymmetry predict a linear dependence of Δv_3 on A_{ch} for pions, similar to that of Δv_2, while the electric quadrupole due to the CMW has no effect on v_3. Therefore, the $\Delta v_3(A_{ch})$ slope, when properly normalized, $\Delta v_n^{norm.} = 2(v_n^- - v_n^+)/(v_n^- + v_n^+)$, provides an estimation of the background contribution to the $\Delta v_2(A_{ch})$ slope.

Fig. 2 compares the normalized $\Delta v_3(A_{ch})$ and $\Delta v_2(A_{ch})$ slopes for pions as a function of centrality in 200 GeV Au+Au collisions. The normalized $\Delta v_3(A_{ch})$ slopes for $0.15 < p_T < 0.5$ GeV/c are lower than or consistent with zero for most centrality intervals, and are systematically below the normalized $\Delta v_2(A_{ch})$ slopes. It is noticed that in semi-central collisions, the normalized slopes between $\Delta v_2(A_{ch})$, $\Delta v_3(A_{ch})$ and CMS results [8] are consistent with each other. However, the large discrepancies in more central and the more peripheral collisions, where the Δv_3 slopes tend to go negative, suggest that the STAR measurements of the $\Delta v_2(A_{ch})$ slopes for pions may not be purely dominated by the LCC effect.

3.3. *The $\Delta v_2(A_{ch})$ slopes for $\pi^{\pm}$ in p+Au, d+Au and U+U collisions*

In small collision systems such as p+Au and d+Au, the orientation of the magnetic field is presumably decoupled from the 2^{nd}-order event plane [7], which makes such small systems an ideal testing ground for the observation of the disappearance of the $\Delta v_2(A_{ch})$ slope. For p+Au and d+Au collisions at 200 GeV, the

[1]The p_T coverage for (anti)proton is (0.4, 2) GeV/c for the sake of statistics

corresponding pion slopes are analyzed with the 2^{nd}-order event plane from TPC and are tested as a function of N_{part}, the number of participating nucleons. The preliminary results of $\Delta v_2(A_{\mathrm{ch}})$ slopes in both p+Au and d+Au are consistent with zero within the uncertainties[2]. The disappearance of the CMW signal in these small systems demonstrates the magnitude of the possible background in the measurement of the CMW at RHIC. The $\Delta v_2(A_{\mathrm{ch}})$ slopes in U+U collisions are slightly higher than the results in Au+Au collisions, which could be qualitatively explained by the CMW picture due to a stronger magnetic field in U+U collisions.

4. Summary

The experimental evidence of the CMW via $\Delta v_2(A_{\mathrm{ch}})$ slope for pions, has been challenged by the isospin effect and the LCC effect. In this work, we present the $\Delta v_2(A_{\mathrm{ch}})$ slopes for low-p_T kaons and protons in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV. The similarity between pion and kaon slopes suggests that the isospin effect is not the dominant contribution to the slopes. The LCC background has been investigated via the normalized $\Delta v_3(A_{\mathrm{ch}})$ slopes, which are typically smaller than the normalized $\Delta v_2(A_{\mathrm{ch}})$ slopes. The measured slopes in the small systems are consistent with zero within the uncertainties as expected. These measurements indicate that the CMW picture stays a viable interpretation of the pion $\Delta v_2(A_{\mathrm{ch}})$ slopes at RHIC.

Acknowledgements

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