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Overview of charge asymmetry dependence of pion elliptic flow and the possible chiral magnetic wave in heavy-ion collisions


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We present measurements of $\pi^-$ and $\pi^+$ elliptic flow, $v_2$, at midrapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6, 11.5$ and 7.7 GeV, as a function of event-by-event charge asymmetry, $A_{ch}$, based on data from the STAR experiment at RHIC. We find that $\pi^-$ ($\pi^+$) elliptic flow linearly increases (decreases) with charge asymmetry for most centrality bins at $\sqrt{s_{NN}} = 27$ GeV and higher. At $\sqrt{s_{NN}} = 200$ GeV, the slope of the difference of $v_2$ between $\pi^-$ and $\pi^+$ as a function of $A_{ch}$ exhibits a centrality dependence, which is qualitatively similar to calculations that incorporate a chiral magnetic wave effect. Similar centrality dependence is also observed at lower energies.

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In heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), energetic spectator protons produce a strong magnetic field reaching $eB_y \approx m^2_\gamma [1]$, or $\sim 3 \times 10^{14}$ T. The interplay between the magnetic field and the quark-gluon matter created in these collisions might result in two phenomena: the chiral magnetic effect (CME) and the chiral separation effect (CSE). The CME is the phenomenon
of electric charge separation along the axis of the magnetic field in the presence of a finite axial chemical potential [16]. The STAR [6–9] and PHENIX [10, 11] Collaborations at the RHIC and the ALICE Collaboration at the LHC [12] have reported experimental observations of charge separation fluctuations, possibly providing evidence for the CME. This interpretation is still under discussion (see e.g. [13–15] and references therein). The CSE refers to the separation of chiral charge, which characterizes left/right handedness, along the axis of the magnetic field in the presence of the finite density of electric charge [16] [17]. In this Letter, we report the results from a search for these effects using a new approach.

In a chirally symmetric phase, the CME and CSE can form a collective excitation, the chiral magnetic wave (CMW). It is a propagation of chiral charge density in a long wavelength hydrodynamic mode [18–20]. The CMW, which requires chiral symmetry restoration, manifests itself in a finite electric quadrupole moment of the collision system. As the colliding nuclei are positively charged, the average charge of the pion is different between $A_r$ than $A_{ch}$ of the pion base [20]. The CMW refers to an azimuthally anisotropic collective motion of soft (low momentum) particles. It is characterized by a second-order harmonic in a particle’s azimuthal distribution, $v_2$, with respect to the reaction plane azimuthal angle, $\Psi_{RP}$, which is determined by the impact parameter and the beam direction,

$$v_2 = \langle \cos[2(\phi - \Psi_{RP})] \rangle.$$  \hspace{1cm} (1)

The CMW is theoretically expected to modify the elliptic flow of charged particles, e.g. pions, on top of the baseline

$$v_2^{base}(\pi^\pm) = v_2^{base}(\pi^+) \pm \frac{r}{2} A_{ch},$$  \hspace{1cm} (2)

where $r$ is the quadrupole moment normalized by the net charge density and $A_{ch} = (N_+ - N_-)/(N_+ + N_-)$ is the charge asymmetry of the collision system. As the colliding nuclei are positively charged, the average charge asymmetry, $A_{ch}$, is always positive. Thus, the $A_{ch}$-integrated $v_2$ of $\pi^-$ ($\pi^+$) should be above (below) the baseline because of the CMW. However, the $v_2^{base}$ may be different between $\pi^+$ and $\pi^-$ because of several other possible physical mechanisms [21–24]. It is preferable to study CMW via the $A_{ch}$ dependence of the pion $v_2$ other than $A_{ch}$-integrated $v_2$.

This Letter reports the $A_{ch}$-differential measurements of the pion $v_2$, based on Au+Au samples of $2 \times 10^8$ events at 200 GeV from RHIC year 2010, 6 $\times 10^7$ at 62.4 GeV (2010), 10$^8$ at 39 GeV (2010), 4.6 $\times 10^7$ at 27 GeV (2011), 2 $\times 10^7$ at 19.6 GeV (2011), 1 $\times 10^7$ for 11.5 (2010) and 4 $\times 10^6$ for 7.7 GeV (2010). All events were obtained with a minimum-bias trigger which selects all particle-producing collisions, regardless of the extent of overlap of the incident nuclei [25]. Charged particle tracks with pseudorapidity $|\eta| < 1$ were reconstructed in the STAR Time Projection Chamber (TPC) [26]. The number of charged particles within $|\eta| < 0.5$ is used to define the centrality. The centrality definitions and track quality cuts are the same as those used in Ref. [27], unless otherwise specified. Only events within 40 cm (50 cm for 11.5 GeV and 70 cm for 7.7 GeV) of the center of the detector along the beam line direction are selected. To suppress events from collisions with the beam pipe (radius = 3.95 cm), a cut on the radial position of the reconstructed primary vertex within 2 cm was applied. A cut on the distance of the closest approach to the primary vertex (DCA < 1 cm) was applied to all tracks to suppress contributions from weak decays and/or secondary interactions.

The observed $A_{ch}$ was determined from the measured charged particles with transverse momentum $p_T > 0.15$ GeV/c and $|\eta| < 1$; protons and anti-protons with $p_T < 0.4$ GeV/c were excluded to reject background protons from the nuclear interactions of pions with inner detector materials. Fig. 1(a) shows an example of the observed $A_{ch}$ distribution, which was divided into five samples roughly containing equal numbers of events, as indicated by the dashed lines. Fig. 1(b) shows the relationship between the observed $A_{ch}$ and the $A_{ch}$ from the HIJING event generator [28], where the same cuts as used in data were applied to calculate $A_{ch}$. The relationship is linear. To select pions with high purity, we eliminate charged particles more than 2$\sigma$ away from the expected energy loss of pions in the TPC. For energies less than or equal to 62.4 GeV, elliptic flow measurements were carried out with the $v_2$ ($v_2^{sub}$) approach [29], where two subevent planes register charged particles with $\eta > 0.3$ and $\eta < -0.3$, respectively. Pions at positive (negative) $\eta$ are then correlated with the subevent plane at negative (positive) $\eta$ to calculate $v_2$. The $\eta$ gap of 0.3 unit suppresses several short-range correlations such as the

![Figure 1](attachment:image.png)

FIG. 1. (Color online) (a) the distribution of observed charge asymmetry from STAR data and (b) the relationship between the observed charge asymmetry and the charge asymmetry from HIJING generated events, for 30–40% central Au+Au collisions at 200 GeV. In this centrality, the mean charge asymmetry $\langle A_{ch} \rangle$ of HIJING events is about 0.004. The errors are statistical only.
Bose-Einstein interference and the Coulomb final-state interactions [30]. There are correlations that are unrelated to the reaction plane that are not suppressed by the $\eta$ gap, e.g. those due to back-to-back jets. These are largely canceled in the $v_2$ difference between $\pi^-$ and $\pi^+$. For 200 GeV, the two-particle cumulant method $v_2 \{2\}$ was employed, which was consistent with $v_2 \{\eta \text{ sub}\}$, and allowed the comparison with the $v_2 \{4\}$ method discussed later in this letter. The same $\eta$ gap was also used in the $v_2 \{2\}$ analysis. To focus on the soft physics regime, only pions with $0.15 < \pt < 0.5$ GeV/$c$ were used to calculate the $\pt$-integrated $v_2$, and this $\pt$ range covers 65-70% of all the produced pions. The calculation of the $\pt$-integrated $v_2$ was corrected with the $\pt$-dependent tracking efficiency for pions.

Taking Au+Au 200 GeV collisions in the 30-40% centrality range as an example, the pion $v_2$ is shown as a function of the observed $A_{ch}$ in Fig. 2(a). The $\pi^-$ $v_2$ increases with increasing observed $A_{ch}$ while the $\pi^+$ $v_2$ decreases with a similar magnitude of the slope. After applying the tracking efficiency to $A_{ch}$, the $v_2$ difference between $\pi^-$ and $\pi^+$ has been fitted with a straight line as shown in Fig. 2(b). The slope parameter, $r$, from Eq. 2, is positive and qualitatively consistent with the expectations of the CMW picture. The fit function is non-zero at the average charge asymmetry $\langle A_{ch}\rangle$, which is a small positive number in case of Au + Au collisions. This indicates the $A_{ch}$-integrated $v_2$ for $\pi^-$ and $\pi^+$ are different, which was observed in Ref. [32]. We follow the same procedure as above to extract the slope parameter, $r$, for all centrality bins at 200 GeV. The results are shown in Fig. 3 together with simulations using the UrQMD event generator [33] and with the theoretical calculations with CMW [34] with different duration times of the magnetic field. For most data points, the slopes are positive and reach a maximum in mid-central/mid-peripheral collisions, a feature also seen in the theoretical calculations of the CMW. The gray bands in Fig. 3 include three types of systematic errors: the DCA cut for pion tracks.
Slope parameter $r$ (%) when convoluted with the characteristic shape of $v$ attention from theorists [34, 37–42]. It was pointed out error. still has a finite positive value with a larger statistical
different duration times. The grey bands carry the same
comparison, we also show the calculations with CMW [34]
FIG. 4. (Color online) The slope parameter $r$ as a function of centrality for all the collision energies under study. For
collisions are consistent with $\langle v_2^2 \rangle$ dependence of $\langle p_T \rangle$. We estimate this contribution to the slope parameter. Recently, a more realistic implementation of the CMW [18] demonstrate a similar centrality dependence of the slope parameter. In summary, pion $v_2$ exhibits a linear dependence on $A_{ch}$, with positive (negative) slopes for $\pi^- (\pi^+)$, $v_2\tau$ exhibits a linear dependence on $A_{ch}$, with positive (negative) slopes for $\pi^- (\pi^+)$. The $v_2(\pi^-) - v_2(\pi^+)$ as a function of $A_{ch}$, suggested a negative slope [45], which is contradictory to the data. The mean field potentials from the hadronic phase [22] and the partonic phase [24] also qualitatively explain the $A_{ch}$-integrated $v_2$ difference between particles and anti-particles, especially at lower beam energies. In general, the mean field potential is expected to be positively correlated with $A_{ch}$ and thus may explain the trends in those data, but no conclusive statement can be made here due to the lack of specific predictions. This effect may be tested in the future by studying the $K^\pm v_2$ slopes, whose $v_2$ ordering is opposite to that of $\pi^\pm$. zero for 10-60% centrality collisions, where the signal is prominent in the data. Similarly, the AMPT event generator [43, 44] also produces events with slopes $r$ consistent with zero. With the AMPT model, we also studied the weak decay contribution to the slope, which was negligible. On the other hand, the CMW calculations [18] demonstrate a similar centrality dependence of the slope parameter.
model. The slope \( r \) of \( V_2(A_{ch}) \) difference between \( \pi^- \) and \( \pi^+ \) has been studied as a function of centrality, and we observe a dependence also similar to the calculation based on the CMW model. The slope parameter \( r \) remains significantly positive for 10 – 60% centrality \( \text{Au+Au} \) collisions at \( \sqrt{s_{NN}} = 27 – 200 \text{ GeV} \), and displays no obvious trend of the beam energy dependence with the current statistics. None of the conventional models discussed, as currently implemented, can explain our observations.

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