Preface

The strong force is one of the four fundamental interactions in particle physics describing the interaction between partons (quarks and gluons) which make up hadrons. The theory of the strong force is called quantum chromodynamics (QCD), which is a quantum field theory of the color charged partons. The force between color charges does not diminish while they are separated. This property causes the color charges to be confined in to hadrons, in ordinary matter. Quark-Gluon Plasma (QGP) is one phase of the QCD matter at extremely high temperature and/or pressure, where the partons are asymptotically free. Experimentally, QGP might be created in ultra relativistic heavy ion collisions [1–4].

It has been suggested that in such deconfined QCD matter, the metastable domains with non-zero topological charge Q_{w} will generate charge separation along the system angular momentum direction caused by chiral magnetic effect (CME). The charge separation direction is random as the sign of Q_{w} is random from domain to domain. The event-by-event charge separation along the system angular momentum direction violates the parity and time-reversal symmetries locally (LPV) [5–10]. In this analysis, we measure the CME/LPV in heavy ion collisions with charge multiplicity asymmetry correlations.

We separate a heavy ion collision event into up and down, or left and right hemispheres according to the reconstructed event-plane and the plane perpendicular to the event-plane. We then calculate the multiplicity asymmetries of the positive and negative charges by taking the multiplicity difference between up and down hemispheres ($A_{\pm,UD}$), as well as left and right hemispheres ($A_{\pm,LR}$), and divide by the total multiplicities. Since the event-plane does not distinguish between up and down nor left and right, the average of the asymmetries are consistent with zero, $\langle A_{\pm,UD}\rangle = \langle A_{\pm,LR}\rangle = 0$. However, the correlations between the asymmetries are non-zero due to the physical correlations between particles.

We study the variances ($\langle A^2_{UD}\rangle$ and $\langle A^2_{LR}\rangle$) and covariances ($\langle A_+A_-\rangle_{UD}$ and $\langle A_+A_-\rangle_{LR}$) of the charge multiplicity asymmetries. The asymmetries are calculated using the multiplicity from one side of the TPC tracks with respect to the event-plane reconstructed from the other side of the TPC tracks in order to avoid self-correlation. We also apply single particle detector efficiency correction on asymmetry calculation and event-plane reconstruction. The variance results are alway positive because they are the square of real numbers, which is the effect of statistical fluctuations. We subtract the statistical fluctuation and the detector non-uniformity effects to obtain the dynamical variances $\delta\langle A_{UD}^2\rangle$ and $\delta\langle A_{LR}^2\rangle$.

We show the dynamical variances and covariances of Au+Au 200 GeV collisions and d+Au 200 GeV collisions. Data show the dynamical variances are positive at peripheral collisions consistent with d+Au data. This suggests that same-sign particle pairs are emitted preferentially in the same direction. Both variances in UD and LR drop in mid-central and central collisions and turn to negative, which suggests that the same-sign pairs are more likely to be emitted symmetrically, more back-to-back in other words, regardless of the directions. The covariances are largely positive for both UD and LR directions, which suggests the opposite-sign particles are strongly correlated, and emitted with small angle correlation.

The CME/LPV expects charge separation across the event-plane (UD direction), which gives additional correlation to the same-sign particle pairs in out-of-plane (UD) direction than in-plane (LR) direction, i.e. a wider distribution of the asymmetries in UD direction. We should expect $\Delta\langle A^2\rangle = \delta\langle A_{UD}^2\rangle - \delta\langle A_{LR}^2\rangle > 0$. One also expects that the positive and negative charges are anti-correlated in UD direction, so that the covariances $\Delta\langle A_+A_-\rangle = \langle A_+A_-\rangle_{UD} - \langle A_+A_-\rangle_{LR}$ are negative. We show the $UD-LR$ correlations of the dynamical variances and covariances. Both the variance and covariance differences are positive for all centralities except the most peripheral bins. The variance $UD-LR$ correlation is positive, which is consistent with CME/LPV expectation. However we also know same-sign pairs are preferentially back-to-back from mid-central to central collisions. The covariance $UD-LR$ correlation is also positive, which is not consistent with the naive expectation of CME/LPV.

We study the transverse momentum (p_T) dependence of the correlations. The CME/LPV expects the charge separation is mostly a low-p_T effect. However data show the correlations increase with p_T in the mid-central collisions.

The dynamical variances and covariance as a function of event-by-event anisotropy v_2^{obs} for low-p_T ($p_T < 2$ GeV/c) and high-p_T ($p_T > 2$ GeV/c) particles are analysed. The $UD-LR$ variance and covariance show opposite trend of low-p_T v_2^{obs}, but with very weak dependence of the high-p_T v_2^{obs}. We use four different data and cuts to verify the result: sub-events with $\eta > 0$ and $\eta < 0$, sub-events with large pseudo-rapidity gap $\eta > 0.5$ and $\eta < -0.5$, events with the first order ZDC-SMD event-plane and top 2 % most central data. They all show similar v_2^{obs} dependence.

There might be charge independent common background sitting between the same-sign and opposite-sign correlations. So we define charge separation as the difference of same-sign and opposite-sign correlations, $\Delta = \Delta\langle A^2\rangle - \Delta\langle A_+A_-\rangle$, to cancel the background, and show it as a function of the wedge size, azimuthal region of the analysed particles. The charge separation vanishes with the decrease of the wedge size, which suggests the charge separation effect is within the vicinity of the reaction-plane.

We also show the charge separation as a function of event-by-event low-p_T v_2^{obs}. The CME/LPV effect does not expect event anisotropy dependence. However, we see the charge separation is strongly and linearly depending on low-p_T v_2^{obs} for four different cases. The linear dependence intercept at zero or slightly positive, when the sub-event is isotropic in low-p_T particle azimuth angle, i.e. $v_2^{obs} = 0$.

Because the average v_2^{obs} is positive due to elliptic flow, the charge separation is positive if we integrate over all events. The linear v_2^{obs} dependence of charge separation is more likely an intrinsic charge dependent bulk correlation of the medium. A more precise measurement of the CME/LPV effect may lie on the events with a more isotropic shape. We show the charge separation of events with $|v_2^{obs}| < 0.04$ as a function of centrality, which is consistent with zero. Thus we give the upper limit of the CME/LPV effect based on the linear fit of the charge separation Δ as a function of v_2^{obs}, that $\Delta = 4.7 \times 10^{-5}$ with 98 % CL.

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