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Fluctuations of charge separation perpendicular to the reaction plane and possible local parity violation in Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 62.4$ GeV

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Local parity-odd domains are theorized to form inside the Quark-Gluon-Plasma (QGP) produced in high energy heavy ion collisions, and to manifest themselves in charge separation perpendicular to the reaction plane via the Chiral Magnetic Effect. Based on the approaches from previous STAR analyses of 200 GeV Au+Au collisions, we further this study into lower collision energies at $\sqrt{s_{NN}} = 7.7 - 62.4$ GeV. The signal gradually changes with decreased beam energy, and tends to diminish around 7.7 GeV. The beam-energy dependency of the $\mathcal{P}$-even background is also discussed.

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A particular domain in the fast-cooling universe after the Big Bang, e.g. the one we live in, may not represent the true ground state. In that case, the domain will predictably collapse into a lower state, with everything inside crushed. Heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) provide a good opportunity to study the domain physics: the collisions are considered as microscopic"Small Bangs", where particular parity-odd ($\mathcal{P}$-odd) domains are theorized to form inside the created Quark-Gluon-Plasma (QGP) [1, 2].

Such $\mathcal{P}$-odd domains can be manifested via the Chiral Magnetic Effect (CME). In heavy ion collisions, mostly energetic spectator protons produce a strong magnetic field peaking around $eB \approx m_\pi^2$ [3], illustrated in Fig. 1. The interplay between the magnetic field and the QGP leads to the electric charge separation along the axis of the magnetic field in the presence of a finite axial chemical potential (e.g. a finite chiral potential due to the local parity violation (LPV) in a $\mathcal{P}$-odd domain) [3–8]. Based on data from STAR [9–11] and PHENIX [12, 13] Collaborations at RHIC and ALICE [14] at LHC, pertinent charge-separation fluctuations were experimentally observed, possibly providing an evidence for the CME and the LPV. This interpretation is still under intense discussion, see e.g. [15, 16] and references therein.

Experimentally the fluctuations of charge separation are measured along the axis of the magnetic field, perpendicular to the reaction plane (containing the impact parameter and the beam momenta), with a three-point correlator, $\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{\rm RP}) \rangle$ [17]. Here ϕ and $\Psi_{\rm RP}$ denote the azimuthal angles of a particle and the reaction plane, respectively. In practice, we approximate the reaction plane with the "event plane" ($\Psi_{\rm EP}$) reconstructed with measured particles, and correct the observed correlation measurement with the event plane resolution [9–11].

This Letter extends the γ measurements of charged particles to Au+Au samples of 8M events at 62.4 GeV (2005), 100M at 39 GeV (2010), 46M at 27 GeV (2011), 20M at 19.6 GeV (2011), 10M at 11.5 GeV (2010) and

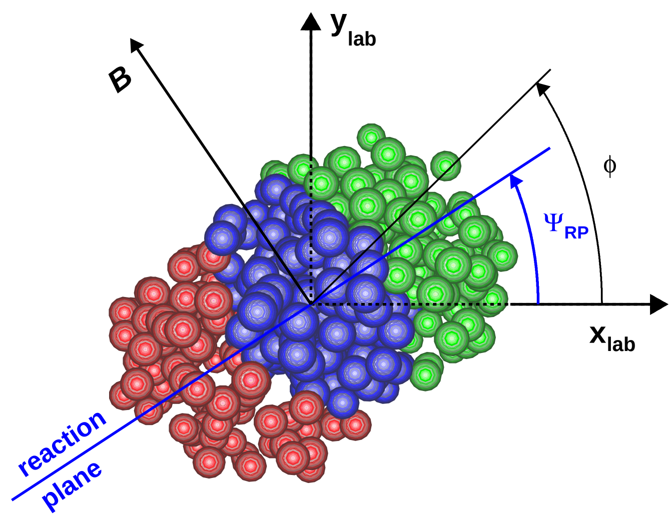

FIG. 1: (Color online) Schematic depiction of the transverse plane in a collision of two heavy ions (one emerging from and one going into the page). Particles are produced out of the overlap region. The azimuthal angles of the reaction plane and a produced particle used in the three-point correlator, γ, are depicted here.

4M at 7.7 GeV (2010). A minimum bias trigger was used with events sorted into centrality classes based on charged particle multiplicity. Charged particle tracks in this analysis were reconstructed in the STAR Time Projection Chamber (TPC) [18], with a pseudorapidity cut $|\eta| < 1$ and a transverse momentum cut $0.15 < p_T < 2$ GeV/c. The centrality definition and track quality cuts are the same as in Ref. [19], unless otherwise specified. Only events within 40 cm of the center of the detector were selected for most data sets. This cut was released to 50 (70) cm for 11.5 (7.7) GeV collisions. 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 < 2 cm) was also applied to reduce the number of weak decay tracks or secondary interactions. The two charged particles involved in the analysis have been corrected for the tracking efficiency.

In an event, charge separation perpendicular to the reaction plane may be described phenomenologically by sine terms in the Fourier decomposition of the charged particle azimuthal distribution

$$\frac{dN_{\pm}}{d\phi} \propto 1+2v_1\cos(\Delta\phi)+2a_{\pm}\sin(\Delta\phi)+2v_2\cos(2\Delta\phi)+... \quad (1)$$

where $\Delta\phi = \phi - \Psi_{\rm RP}$. Conventionally v_1 is called "directed flow" and v_2 "elliptic flow", and they describe the collective motion of the produced particles [20]. The a parameters, $a_- = -a_+$, quantifies the $\mathcal{P}$-violating effect. The predicted spontaneous parity violation requires that the sign of a_+ and a_- should vary from event to event, leading to $\langle a_+\rangle = \langle a_-\rangle = 0$. However, the expansion of the correlator, $\gamma = \langle\cos(\Delta\phi_1)\cos(\Delta\phi_2) - \sin(\Delta\phi_1)\sin(\Delta\phi_2)\rangle$ contains the fluctuation term $\langle a_{\pm}a_{\pm}\rangle$, which may be non-zero when accumulated over particle pairs of separate charge combinations. The $\langle v_1 v_1\rangle$ term in the expansion provides a baseline unrelated to the reaction plane orientation.

The reaction plane of a heavy-ion collision is not known a priori, and in practice it is approximated with the event plane reconstructed from particle azimuthal distributions [20]. In this analysis, we exploited the large elliptic flow of charged hadrons produced at mid-rapidity:

$$\Psi_{\rm EP} = \frac{1}{2}\tan^{-1}\left[\frac{\sum\omega_i\sin(2\phi_i)}{\sum\omega_i\cos(2\phi_i)}\right], \quad (2)$$

where ω_i is a weight for each particle i in the sum [20]. The weight was chosen to be the p_T of the particle itself. Although the STAR TPC has good azimuthal symmetry, small acceptance effects in the calculation of the event plane azimuth were removed by the method of shifting [21]. The observed correlations were corrected for the event plane resolution, estimated with the correlation between two random sub-events (details in Ref. [20]).

The event plane thus obtained from the produced particles is also called "the participant plane" since it is subject to the event-by-event fluctuations of the initial participant nucleons [22]. A better approximation to the reaction plane could be obtained from the spectator neutron distributions detected in the STAR ZDC-SMD [23]. This type of event plane utilizes the directed flow of spectator neutrons measured at very forward rapidity. As to the three-point correlator, measurements carried out with both types of event planes turned out to be consistent with each other [11]. Other systematic uncertainties were studied extensively in the previous publications on this subject [9, 10]. All were shown to be negligible compared with the uncertainty in determining the reaction plane. In this work, we only used the participant plane

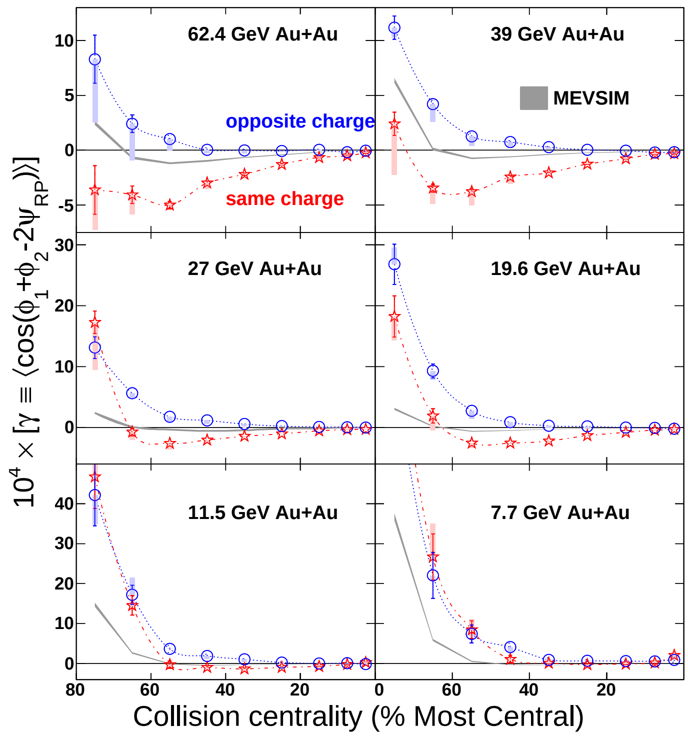

FIG. 2: (Color online) The three-point correlator as a function of centrality for Au+Au collisions at 7.7-62.4 GeV. Note that the vertical scales are different for different rows. The unidirectional systematic errors (filled boxes) reflect the extra conditions of $\Delta p_T > 0.15$ GeV/c and $\Delta\eta > 0.15$ to suppress HBT+Coulomb effects (to be discussed later).

because the efficiency of ZDC-SMD becomes very low for low beam energies.

Figure 2 presents the opposite-charge ($\gamma_{\rm OS}$) and same-charge ($\gamma_{\rm SS}$) correlators for Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 62.4$ GeV as a function of centrality (0 means the most central collisions). In most cases, the ordering of $\gamma_{\rm OS}$ and $\gamma_{\rm SS}$ is still present as in Au+Au (Pb+Pb) collisions at higher energies [9–11, 14], manifesting extra charge-separation fluctuations perpendicular to the reaction plane. As a systematic check, the charge combinations of ++ and −− are always found to be consistent with each other (not shown here). With decreased beam energy, both $\gamma_{\rm OS}$ and $\gamma_{\rm SS}$ tend to rise up starting from peripheral collisions. This feature seems to be charge independent, and can be explained by momentum conservation and elliptic flow [11]. Momentum conservation forces all produced particles, regardless of charge, to separate from each other, while elliptic flow works in the opposite sense. For peripheral collisions, the multiplicity (N) is small, and momentum conservation dominates. The lower beam energy, the smaller N, and the higher $\gamma_{\rm OS}$ and $\gamma_{\rm SS}$. For more central collisions where the multiplicity is large enough, this type of $\mathcal{P}$-even background can be estimated with $-v_2/N$ [11, 24]. MEVSIM is a

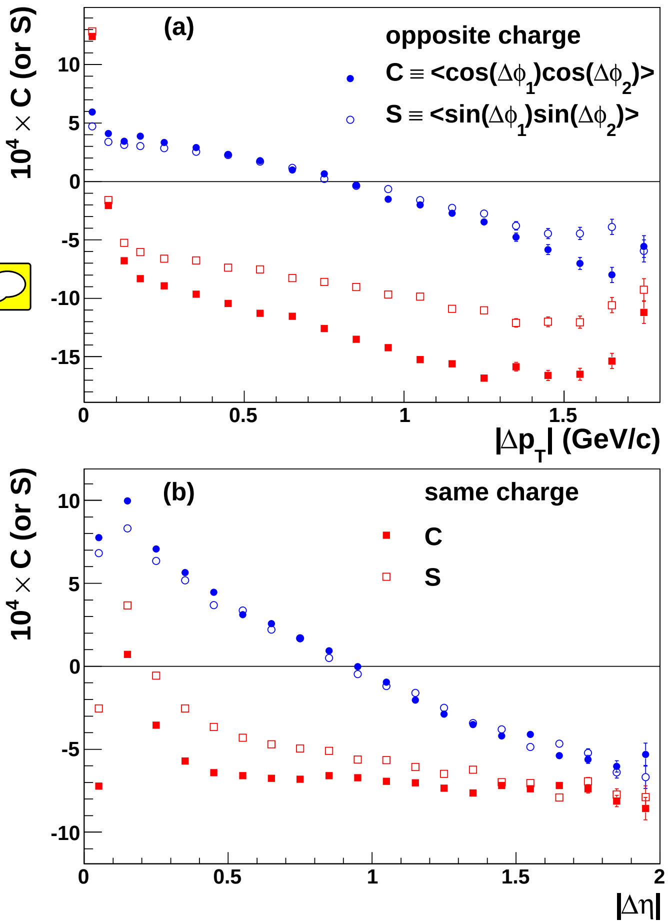

FIG. 3: (Color online) Three-point correlations split up into in-plane and out-of-plane composite parts for $30-60\%$ Au+Au collisions at 39 GeV. (a) shows the correlations versus $|\Delta p_T| = |p_{T,1} - p_{T,2}|$. (b) shows the correlations versus $|\Delta\eta| = |\eta_1 - \eta_2|$. The error bars are statistical only.

Monte Carlo event generator developed for STAR simulations [25]. In Fig. 2, we also show the model calculations of MEVSIM with the implementation of v_2 and momentum conservation, which qualitatively describe the beam-energy dependency of the charge-independent background.

In view of the charge-independent background, the charge separation effect can be studied via the difference between $\gamma_{\rm OS}$ and $\gamma_{\rm SS}$. $(\gamma_{\rm OS} - \gamma_{\rm SS})$ remains positive for all centralities down to the beam energy $\sim$ 19.6 GeV, and the magnitudes decrease from peripheral to central collisions. Presumably this is partially owing to the reduced magnetic field and partially owing to the more servere dilution effect in more central collisions [10]. The difference approaches zero in peripheral collisions at lower energies, especially at 7.7 GeV, which is understandable in the picture of LPV and CME as the formation of QGP becomes less likely in peripheral collisions at low energies [26].

The systematic uncertainties of $(\gamma_{\rm OS} - \gamma_{\rm SS})$ due to the analysis cuts, the tracking efficiency and the event plane determination were estimated to be relative 10%, 5% and 10%, respectively. Overall, total systematic uncertainties are typically within 15% when $(\gamma_{\rm OS} - \gamma_{\rm SS})$ is not close to zero. Another type of uncertainties, due to known physics, will be discussed below. Figure 3 takes $30-60\%$ Au+Au collisions at 39 GeV as an example, to show the composite parts of the three-point correlator differentially versus (a) $|\Delta p_T|$ and (b) $|\Delta\eta|$. The subtraction of out-of-plane ($\langle\sin(\Delta\phi_1)\sin(\Delta\phi_2)\rangle$) from in-plane ($\langle\cos(\Delta\phi_1)\cos(\Delta\phi_2)\rangle$) composite parts yields the original γ, while the sum yields a two particle correlation, $\delta \equiv \langle\cos(\phi_1 - \phi_2)\rangle$. The split correlations reveal the underlying $\mathcal{P}$-even background affecting both composite parts as each part is sensitive to correlations independent of the reaction plane. For both $\gamma_{\rm OS}$ and $\gamma_{\rm SS}$, the functional shape of in-plane and out-of-plane parts are similar. The magnitudes of in-plane and out-of-plane parts are more different for same charge pairs.

In the lowest bins in Fig. 3, shape changes are visible for same charge pairs in panel (a) and for both opposite and same charge pairs in panel (b). Such changes can be attributed to quantum interference ("HBT" effects) and final-state-interactions (Coulomb dominated) [11], which are most prominent for low relative momentum. To suppress the contributions from these effects, we applied the conditions of $\Delta p_T > 0.15$ GeV/c and $\Delta\eta > 0.15$ to the three-point correlator, shown with unidirectional filled boxes in Figs. 2 and 4.

To suppress the flow contribution in $(\gamma_{\rm OS} - \gamma_{\rm SS})$, we take the assumption suggested by Ref [27]:

$$\gamma \equiv \langle\cos(\phi_1 + \phi_2 - 2\Psi_{\rm RP})\rangle = v_2 F - H \quad (3)$$

$$\delta \equiv \langle\cos(\phi_1 - \phi_2)\rangle = F + H \quad (4)$$

where F and H are the flow and CME contributions, respectively. With γ and δ measured here and v_2 from previous publications [19], we can solve for H. Figure 4 shows $H_{\rm SS}$ and $H_{\rm OS}$ separately for $30-60\%$ Au+Au collisions (upper), and $(H_{\rm SS} - H_{\rm OS})$ for different centralities (middle and lower) as a funtion of beam energy. For comparison, the results for $10-60\%$ centrality ranges are also shown for Pb+Pb collisions at 2.76 TeV [14]. In general, both $H_{\rm SS}$ and $H_{\rm OS}$ are still influenced by momentum conservation, and $(H_{\rm SS} - H_{\rm OS})$ demonstrates a weak energy dependency above 19.6 GeV. From 19.6 to 7.7 GeV, $(H_{\rm SS} - H_{\rm OS})$ tends to diminish, though the statistical errors are large for 7.7 GeV. This may be explained by the probable domination of hadronic interactions over partonic ones at low energies.

In summary, a three-point correlation between two charged particles and the reaction plane has been carried out for Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 62.4$ GeV. The general trend of separate correlations ($\gamma_{\rm OS}$ and $\gamma_{\rm SS}$) as a function of centrality and beam energy can be qualitatively described by the model calculations of MEVSIM, indicating the $\mathcal{P}-$even background due to

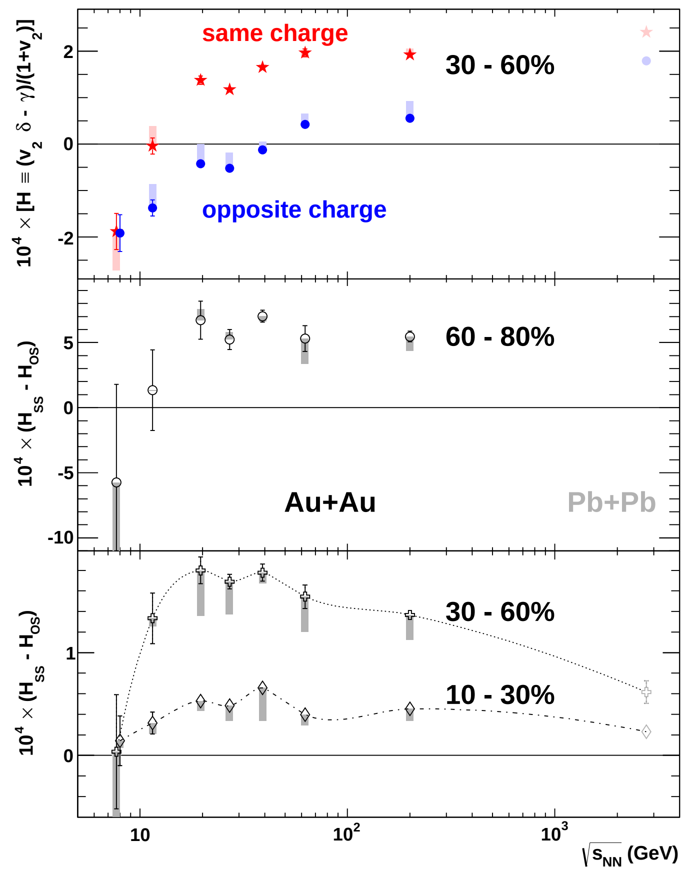

FIG. 4: (Color online) The presumable CME contribution, $H_{\rm SS}$ and $H_{\rm OS}$, as a function of beam energy for $30-60\%$ Au+Au collisions (upper), and $(H_{\rm SS}-H_{\rm OS})$ for three centrality bins (middle and lower). For comparison, the results for Pb+Pb collisions at 2.76 TeV are also shown [14]. The unidirectional systematic errors of the STAR data (filled boxes) are obtained with the conditions of $\Delta p_T > 0.15$ GeV/c and $\Delta\eta > 0.15$ to suppress HBT+Coulomb effects.

momentum conservation and collective flow. The charge separation perpendicular to the reaction plane was studied via $(H_{\rm SS}-H_{\rm OS})$, which shows a weak energy dependency down to 19.6 GeV and then falls at lower energies. This is coherent with the picture of local parity violation and chiral magnetic effect when the hadronic phase plays an increased role with decreased energy. The results will be more conclusive in future if we could increase the statistics by ten times for the low energies.

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