Title
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Permalink
https://escholarship.org/uc/item/8nj1w0qc

Journal
Physical review letters, 113(5)

ISSN
0031-9007

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Publication Date
2014-08-01

DOI
10.1103/physrevlett.113.052302

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Peer reviewed
Beam-energy dependence of charge separation along the magnetic field in Au+Au collisions at RHIC

Local parity-odd domains are theorized to form inside a Quark-Gluon-Plasma (QGP) which has been produced in high-energy heavy-ion collisions. The local parity-odd domains manifest themselves as charge separation along the magnetic field axis via the chiral magnetic effect (CME). The experimental observation of charge separation has previously been reported for heavy-ion collisions.
at the top RHIC energies. In this paper, we present the results of the beam-energy dependence of the charge correlations in Au+Au collisions at midrapidity for center-of-mass energies of 7.7, 11.5, 19.6, 27, 39 and 62.4 GeV from the STAR experiment. After background subtraction, the signal gradually reduces with decreased beam energy, and tends to vanish by 7.7 GeV. This implies the dominance of hadronic interactions over partonic ones at lower collision energies.

PACS numbers: 25.75.-q

The strong interaction is parity even at vanishing temperature and isospin density $\overline{1}$, but parity could be violated locally in microscopic domains in QCD at finite temperature as a consequence of topologically non-trivial configurations of gauge fields $\overline{2}, \overline{3}$. The Relativistic Heavy Ion Collider (RHIC) provides a good opportunity to study such parity-odd ($P$-odd) domains, where the local imbalance of chirality results from the interplay of these topological configurations with the hot, dense and deconfined Quark-Gluon-Plasma (QGP) created in heavy-ion collisions.

The $P$-odd domains can be manifested via the chiral magnetic effect (CME). In heavy-ion collisions, energetic protons (mostly spectators) produce a magnetic field ($B$) with a strength that peaks around $eB \approx 10^4$ MeV$^2$ $\overline{3}$. The magnetic field is illustrated in Fig. 1. The strong magnetic field, coupled with the chiral asymmetry in the $P$-odd domains, induces a separation of electric charge along the direction of the magnetic field $\overline{4}$. Based on data from the STAR $\overline{10}, \overline{13}$ and PHENIX $\overline{14}, \overline{15}$ collaborations at RHIC and the ALICE collaboration $\overline{16}$ at the LHC, charge-separation fluctuations have been experimentally observed. The interpretation of these data as an indication of the CME is still under intense discussion, see e.g. $\overline{13}, \overline{17}, \overline{18}$ and references therein. A study of the beam-energy dependence of the charge separation effect will shed light on the interpretation of the data.

The magnetic field axis points in the direction that is perpendicular to the reaction plane, which contains the impact parameter and the beam momenta. Experimentally the charge separation is measured perpendicularly to the reaction plane with a three-point correlator, $\overline{2}$, and denoted by the azimuthal angles of the reaction plane and a produced particle $\overline{1}$. The azimuthal angles of a particle and the reaction plane, respectively. In practice, we approximate the reaction plane by the "event plane" ($\Psi_{RP}$) reconstructed with measured particles, and then correct the measurement for the finite event plane resolution $\overline{10}, \overline{12}$.

This Letter reports measurements of the three-point correlator, $\gamma$, for charged particles produced in Au+Au collisions. 8M events were analyzed at the center-of-mass energy $\sqrt{s_{NN}} = 62.4$ 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 4M at 7.7 GeV (2010). Events selected with a minimum bias trigger have been sorted into centrality classes based on uncorrected charged particle multiplicity at midrapidity. Charged particle tracks in this analysis were reconstructed in the STAR Time Projection Chamber (TPC) $\overline{20}$, within a pseudorapidity range of $|\eta| < 1$ and a transverse momentum range of $0.15 < p_T < 2$ GeV/$c$. The centrality definition and track quality cuts are the same as in Refs. $\overline{21}$, unless otherwise specified. Only events within 40 cm of the center of the detector along the beam direction were selected for data sets at $\sqrt{s_{NN}} = 19.6 - 62.4$ GeV. This cut was 50 and 70 cm for 11.5 and 7.7 GeV collisions, respectively. To suppress events from collisions with the beam pipe (radius 3.95 cm), only those events with a radial position of the reconstructed primary vertex within 2 cm were analyzed. A cut on the distance of closest approach to the primary vertex (DCA) < 2 cm was also applied to reduce the number of weak decay tracks or secondary interactions. The experimental observables involved in the analysis have been corrected for the particle track reconstruction efficiency.

In an event, charge separation along the magnetic field (i.e., perpendicular to the reaction plane) may be described phenomenologically by a sine term in the Fourier decomposition of the charged particle azimuthal distribution,

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

(1)

where $\Delta\phi = \phi - \Psi_{RP}$, and the subscript $\alpha$ (+ or −) de-
the second term contains the fluctuation term of separate charge combinations. The first term elliptic flow of charged hadrons produced at mid-rapidity plane which is reconstructed from particle azimuthal distribution occurs, the signs of finite violating effect. However, if spontaneous parity violation occurs, the signs of finite explicitly violates parity. In this work, we have only used the participant plane because the efficiency of ZDC-SMDs becomes low for low beam energies.

Figure 2 presents the opposite-charge ($\gamma_{OS}$) and same-charge ($\gamma_{SS}$) 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 $\gamma_{OS}$ and $\gamma_{SS}$ is the same as Au+Au collisions at higher energies [12]. With decreased beam energy, both $\gamma_{OS}$ and $\gamma_{SS}$ tend to rise up in peripheral collisions. This feature seems to be charge independent, and can be explained by momentum conservation and elliptic flow [12].

The reaction plane of a heavy-ion collision is not known priori, and in practice it is approximated with an event plane which is reconstructed from particle azimuthal distributions [22]. In this analysis, we exploited the large elliptic flow of charged hadrons produced at mid-rapidity to construct the event plane angle:

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

where $\omega_i$ is a weight for each particle $i$ in the sum [22].

The weight was chosen to be the $p_T$ of the particle itself, and only particles with $p_T < 2$ GeV/c were used. 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 [23]. The observed correlations were corrected for the event plane resolution, estimated with the correlation between two random sub-events (details in Ref. [22]).

The event plane thus obtained from the produced particles is sometimes called “the participant plane” since it is subject to the event-by-event fluctuations of the initial participant nucleons [24]. A better approximation to the reaction plane could be obtained from the spectator neutron distributions detected in the STAR zero degree calorimeters (ZDC-SMDs) [25]. This type of event plane utilizes the directed flow of spectator neutrons measured at very forward rapidity. We have measured the three point correlations using both types of reaction plane estimates and the results are consistent with each other [12]. Other systematic uncertainties were studied extensively and discussed in our previous publications on the subject [10, 11]. All were shown to be negligible compared with the uncertainty in determining the reaction plane.

In this work, we have only used the participant plane because the efficiency of ZDC-SMDs becomes low for low beam energies.
ence between $\gamma_{\text{OS}}$ and $\gamma_{\text{SS}}$. The difference $(\gamma_{\text{OS}} - \gamma_{\text{SS}})$ remains positive for all centralities down to the beam energy $\sim 19.6$ GeV, and the magnitude decreases from peripheral to central collisions. Presumably this is partially owing to the reduced magnetic field and partially owing to the more pronounced dilution effect in more central collisions. A dilution of the correlation is expected when there are multiple sources involved in the collision [11, 29]. The difference between $\gamma_{\text{OS}}$ and $\gamma_{\text{SS}}$ approaches zero in peripheral collisions at lower energies, especially at 7.7 GeV, which could be understood in terms of the CME hypothesis if the formation of the QGP becomes less likely in peripheral collisions at low beam energies [30].

The systematic uncertainties of $(\gamma_{\text{OS}} - \gamma_{\text{SS}})$ due to the analysis cuts, the track reconstruction efficiency and the event plane determination were estimated to be approximately 10%, 5% and 10%, respectively. Overall, total systematic uncertainties are typically 15%, except for the cases where $(\gamma_{\text{OS}} - \gamma_{\text{SS}})$ is close to zero. Another type of uncertainty is due to quantum interference (“HBT” effects) and final-state-interactions (Coulomb dominated) [12], which are most prominent for low relative momenta. 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 correlations, shown as filled boxes in Figs. 2, 3 and 4. The boxes start from the central values with default conditions and end with the results with the above extra conditions on $\Delta p_T$ and $\Delta \eta$.

Interpretation of the three particle correlation result, $\gamma$, requires additional information such as a measurement of the two particle correlation $\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = \langle \cos(\Delta \phi_1) \cos(\Delta \phi_2) + \sin(\Delta \phi_1) \sin(\Delta \phi_2) \rangle$. The expansion of $\delta$ also contains the fluctuation term $\langle a_+ a_- \rangle$ (with a sign opposite to that in $\gamma$). Figure 3 shows $\delta$ as a function of centrality for Au+Au collisions at 7.7–62.4 GeV. In contrary to the CME expectation, $\delta_{\text{OS}}$ is above $\delta_{\text{SS}}$ in most cases, indicating an overwhelming background, larger than any possible CME effect. The background sources, if coupled with collective flow, will also contribute to $\gamma$. Taking this into account, we express $\gamma$ and $\delta$ in the following forms, where the unknown parameter $\kappa$, as argued in Ref. [31], is of the order of unity.

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

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

where $H$ and $F$ are the CME and background contributions, respectively. In Ref. [31] $\kappa = 1$, but it could deviate from unity owing to a finite detector acceptance and theoretical uncertainties. We can solve for $H$ from Eqns. 3 and 4

$$H^\kappa = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2).$$

Figure 4 shows $H_{\text{SS}} - H_{\text{OS}}$ as a function of beam energy for three centrality bins in Au+Au collisions. $v_2$ for the beam energies under study has been measured in our previous publications [21]. The default values (dotted curves) are for $H^\kappa = 1$, and the solid (dash-dot) curves are obtained with $\kappa = 1.5$ ($\kappa = 2$). For comparison, the results for 10–60% Pb+Pb collisions at 2.76 TeV are also shown [16]. The $(H_{\text{SS}} - H_{\text{OS}})$ curve for $\kappa = 1$ suggests a non-zero charge separation effect with a weak energy dependence above 19.6 GeV, but the trend rapidly decreases to zero in the interval between 19.6 and 7.7 GeV. This may be explained by the probable domination of hadronic interactions over partonic ones at low beam energies. With increased $\kappa$, $(H_{\text{SS}} - H_{\text{OS}})$ decreases for all beam energies and may even totally disappear in some case (e.g. with $\kappa \sim 2$ in 10–30% collisions). A better theoretical estimate of $\kappa$ in the future would enable us to extract a firmer conclusion from the data presented.

MEVSIM calculations qualitatively reproduce the charge-independent background for both $\gamma$ and $\delta$ correlators as shown in Figs. 2 and 4, but they always yield identical same-charge and opposite-charge correlations. To further study the charge separation effect, a transport model, UrQMD [28], was employed. UrQMD calculations have finite difference between same-charge and opposite-charge $\gamma$ ($\delta$) correlations, while $H_{\text{SS}} - H_{\text{OS}}$ is either slightly negative or consistent with zero. This is demonstrated for 27 and 39 GeV in Figs. 4 and 4.
FIG. 4: $H_{SS} - H_{OS}$, as a function of beam energy for three centrality bins in Au+Au collisions. The default values (dotted curves) are for $H^*=1$, and the solid (dash-dot) curves are obtained with $\kappa = 1.5$ ($\kappa = 2$). For comparison, the results for Au+Au collisions at 200 GeV [11] and Pb+Pb collisions at 2.76 TeV [16] are also shown. The systematic errors of the STAR data (filled boxes) bear the same meaning as those in Fig. 2. UrQMD calculations with $\kappa$ = 1 are also shown as solid shaded bars for 27 and 39 GeV.

In summary, an analysis of the 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 the correlation ($\gamma_{OS}$ and $\gamma_{SS}$), as a function of centrality and beam energy, can be qualitatively described by the model calculations of MEVSIM. This result indicates a large contribution from the $P$-even background due to momentum conservation and collective flow. The charge separation along the magnetic field, studied via $H_{SS} - H_{OS}$, shows a signal with a weak energy dependence down to 19.6 GeV and then falls steeply at lower energies. This trend may be consistent with the hypothesis of local parity violation because there should be a smaller probability for the CME at lower energies where the hadronic phase plays a more dominant role than the partonic phase. A more definitive result may be obtained in the future if we can increase the statistics by a factor of ten for the low energies and if we can reduce the uncertainty associated with determination of the value of $\kappa$.

We thank the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL, the KISTI Center in Korea, and the Open Science Grid consortium for providing resources and support. This work was supported in part by the Offices of NP and HEP within the U.S. DOE Office of Science, the U.S. NSF, CNRS/IN2P3, FAPESP CNPq of Brazil, the Ministry of Education and Science of the Russian Federation, NNSFC, CAS, MoST and MoE of China, the Korean Research Foundation, GA and MSMT of the Czech Republic, FIAS of Germany, DAE, DST, and CSIR of India, the National Science Centre of Poland, National Research Foundation (NRF-2012040424), the Ministry of Science, Education and Sports of the Republic of Croatia, and RosAtom of Russia.


