Search for local parity violation with STAR
ZDC-SMD

Gang Wang (for the STAR Collaboration)
Department of Physics and Astronomy, University of California, Los Angeles, CA 90095 U.S.A.
E-mail: gwang@physics.ucla.edu

Abstract. Parity-odd domains are predicted to lead to charge separation of quarks along the
orbital momentum of the system created in non-central relativistic heavy ion collisions. A
signal consistent with several of the theoretical expectations has been detected by STAR, with
a three particle azimuthal correlator which is a $P$-even observable, but still sensitive to the
charge separation effect. In this correlator, the first two particles are used to reveal the physics
of interest, and the third particle serves as a reference for the reaction plane. In this work,
to minimize the non-parity correlation between the third particle and the first two, we utilize
the spectator neutrons detected by STAR ZDC-SMDs to define the event plane. The 1st-order
event plane thus obtained can also be used to study the global strong parity violation effect,
and to provide further systematic checks for this analysis. We report measurements of both
$P$-even and $P$-odd observables using the STAR ZDC-SMDs in $Au+Au$ at 200 GeV. The results
are presented as a function of collision centrality, particle separation in rapidity and transverse
momentum ($p_T$). Systematic checks on the impact from the directed flow will also be discussed.

1. Introduction
The concept of local parity ($P$) violation in high-energy heavy ion collisions was brought up by
Lee et al. [1, 2, 3] and elaborated by Kharzeev et al. [4]. Recently it was argued [5] that in non-
central collisions such a $P$-odd domain can manifest itself via preferential same charge particle
emission for particles moving along the system’s angular momentum, due to the strong magnetic
field produced in the collision. Phenomenologically, the charge separation can be described by
adding $P$-odd sine terms to the Fourier decomposition of the particle azimuthal distribution with
respect to the reaction plane angle, $\Psi_{RP}$, which is often used in the description of anisotropic
flow:

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

where $\Delta \phi = \phi - \Psi_{RP}$ is the particle azimuthal angle relative to the reaction plane, $v_1$ and $v_2$
are coefficients, assumed here to be the same for positive and negative particles, accounting for
the so-called directed and elliptic flow, respectively. The $a$ parameters, $a_- = -a_+$, are $P$-odd
quantities, and describe the $P$-violating effect.

According to the theory, the sign of $a_\pm$ varies event to event following the fluctuations in the
domain’s topological charge, so $\langle a_\pm \rangle$ must be zero, and the observation of the effect is possible
only via correlations, e.g. measuring $\langle a_\alpha a_\beta \rangle$, where $\alpha$ and $\beta$ denote the particle type. To study
this effect, a three particle mixed harmonics azimuthal correlator was proposed [6]:

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle v_{1,\alpha} v_{1,\beta} + B_{in} \rangle - \langle (a_\alpha a_\beta) + B_{out} \rangle,$$

(2)
which is a $P$-even observable, but can be sensitive to the charge separation effect. The $\langle v_{1,\alpha} v_{1,\beta} \rangle$ term should vanish when measured over a rapidity region symmetric around zero, since $v_1$ is an anti-symmetric function of rapidity. $B_{\text{out}}$ represents all other (than parity violation) contributions by correlations projected onto the direction perpendicular to the reaction plane ("out of plane"). The effects contributing to $B_{\text{out}}$ may be large and are difficult to estimate reliably. $B_{\text{in}}$ is the contribution of the in-plane correlations which are analogous to $B_{\text{out}}$. $B_{\text{in}}$ and $B_{\text{out}}$ contain correlations not related to the reaction plane orientation, and they largely cancel out. Only the parts of such correlations that depend on azimuthal orientation with respect to the reaction plane remain as backgrounds.

To minimize the reaction-plane independent backgrounds produced by direct three (or more) particle clusters, we utilize the spectator neutrons detected by the Shower Maximum Detectors (SMD) of the Zero Degree Calorimeters (ZDC) [7] to define the event plane in STAR. The advantage of the event plane from the ZDC over that from the TPC [8] lies in the large rapidity gap between the spectators and the particles of interest in the analysis. Furthermore, the spectator $v_1$ helps estimate the first-order event plane, instead of the second-order event plane from $v_2$ measured in TPC, so that the global $P$-violation quantity $\langle a \rangle$ can be directly measured, and the systematics from the $\langle v_{1,\alpha} v_{1,\beta} \rangle$ term can be studied.

In the following sections, we will compare the correlator measured in STAR as a function of centrality with the event plane from ZDC, along with the STAR published results where the reaction plane is approximated with a third particle from TPC [9]. The vanishing of the $\langle a \rangle$ and $\langle v_{1,\alpha} v_{1,\beta} \rangle$ terms will also be demonstrated. If the two particles truly come from the same $P$-odd domain, we expect them to be close to each other in rapidity space and momentum space. The correlator as functions of the pseudo-rapidity gap and of the transverse momentum gap will thus be discussed.

2. Data sets and analyses
This study is based on 36 million 200 GeV Au+Au events taken during RHIC run VII (2007). Charged particle tracks were reconstructed in STAR’s main TPC, with pseudo-rapidity coverage $|\eta| < 1.3$. The centrality definition (in which zero represents the most central collisions) is the same as in Ref. [10], and the track quality cuts are the same as in Ref. [9]. The reconstruction and utilization of the first-order event plane from STAR ZDC-SMDs has previously been extensively discussed [11, 12, 13]. Due to the poor event plane resolution in $0 - 10\%$ collisions [14], we only show results for $10\% - 80\%$ collisions in this work.

3. Results and discussions
In practice, we use an event plane (an estimated reaction plane) or a third particle to approximate the reaction plane $\Psi_{RP}$ in Eq. (2), and then correct the measurement with the event plane resolution or the $v_2$ of the third particle. Figure 1 shows the correlator as a function of centrality in 200 GeV Au+Au collisions, with the third particle from STAR TPC [9] and the event plane estimated from ZDC. The consistency between the results with different reaction plane approximations (and very different correction factors for the event plane resolution or $v_2$) illustrates that the measured correlator is truly related to the reaction plane orientation, and that the non-flow/non-parity three-particle correlations largely cancel out between $B_{\text{in}}$ and $B_{\text{out}}$. The like- and unlike-sign correlations clearly exhibit very different behaviors. According to Eq. (2), a negative value of the correlator for the like-sign particle pairs means a positive correlation between them with respect to the reaction plane, or in other words that they tend to be emitted to the same side of the reaction plane. On the other hand, a positive value of the correlator for the unlike-sign pairs means that they go to the opposite sides. The difference between the like-sign and unlike-sign pairs is consistent with the charge separation with respect to the reaction plane. The fact that the correlator for the unlike-sign pairs is close to zero for
negatively charged particles in the same events where the correlator is calculated, and it will have a finite contribution to the correlator. We have measured can factorize the with a straight line function for each centrality. If \(P\) measured \(h\) and \(v\) and \(v\) and it will have a finite contribution to the correlator. We have measured can factorize the with a straight line function for each centrality. If \(P\) measured \(h\) and \(v\) and it will have a finite contribution to the correlator. We have measured can factorize the with a straight line function for each centrality. If \(P\) measured \(h\) and \(v\) and it will have a finite contribution to the correlator.

most centrality bins, instead of a similar magnitude as that for the like-sign pairs, could be explained by the suppression of back-to-back correlations due to the medium [15].

The correlations are weaker in more central collisions compared with more peripheral collisions, which can be attributed partially to the dilution of correlations in the case of particle production from multiple sources. If more than one \(P\)-odd domain is created in the medium, and the sign of \(a_\pm\) in each domain fluctuates, the superposition of the correlations from different domains acts like a random walk. In a random walk of \(N\) steps, the final position \(R\) follows a Gaussian distribution with the expectation to be 0 and the RMS to be \(\sqrt{N}\) at large \(N\). Our measurement of the \(P\)-even quantity is in analogy to \(R^2\) which has an expectation of \(N\) according to the Gaussian distribution. Compared with going in a fixed direction, where \(R^2 = N^2\), the random-walk observable is diluted by a factor of \(N\). As to our measurement, \(N\) here is the number of \(P\)-odd domains in one event. In practice, we assume \(N\) is proportional to the number of participants \((N_{\text{part}})\) in the following compensation for this effect. To present a more complete picture of the centrality dependence, we show in Fig. 2 results multiplied by \(N_{\text{part}}\) [9]. The decrease of the correlations in the most central collisions is expected as the magnetic field weakens. The like- and unlike-sign correlations in the peripheral Au+Au collisions where the medium is thin, are found to be at similar magnitudes. This supports the picture of the suppression of back-to-back correlations due to the dense medium leading to the difference in the magnitudes of like- and unlike-sign correlations in central collisions [15]. The negative values of the unlike-sign correlator in central collisions may be caused by some residual non-\(P\) effects, such as radial flow.

The global \(P\)-violation effect has also been investigated with the first-order event plane, and the \(P\)-odd quantities \(\langle a_\pm \\rangle\) are plotted in Fig. 3 as a function of centrality. Within errors, the measured \(\langle a_+ \rangle\) is consistent with \(\langle a_- \rangle\), supporting the picture of the random fluctuations in the \(P\)-odd domain’s topological charge. In most centrality bins, the values of \(\langle a_\pm \rangle\) are on the order of \(10^{-4}\), leading to a negligible contribution (\(\sim 10^{-8}\)) to the correlator.

If \(v_1(\eta)\) is not anti-symmetric around \(\eta = 0\), then the \(\langle v_{1,\alpha} v_{1,\beta} \rangle\) term in Eq. (2) will not vanish, and it will have a finite contribution to the correlator. We have measured \(v_1(\eta)\) for positively and negatively charged particles in the same events where the correlator is calculated, and fit \(v_1(\eta)\) with a straight line function for each centrality. If \(v_{1,\alpha}\) and \(v_{1,\beta}\) are independent of each other, we can factorize the \(\langle v_{1,\alpha} v_{1,\beta} \rangle\) term as \(\langle v_{1,\alpha} \rangle \langle v_{1,\beta} \rangle\). The slope of the fit function has no contributions.
to the integration over a symmetric $\eta$ range. The intercept of the fit quantifies the deviation of directed flow from anti-symmetry due to non-flow effects such as momentum conservation and Coulomb effects. The $v_1(\eta)$ intercept is shown in percentage in Fig. 4 as a function of centrality. The intercept is consistent with zero in all centrality bins, and has a similar magnitude with $(a_\pm)$, and thus a similarly negligible contribution to the correlator. If $v_{1,\alpha}$ and $v_{1,\beta}$ have correlations between them other than flow-wise, such as non-flow effects produced by direct two particle clusters, then the $\langle v_{1,\alpha}v_{1,\beta} \rangle$ term contains an extra reaction-plane independent background. From the above experience of the direct three (or more) particle clusters, we expect a similar background in the $\langle a_\alpha a_\beta \rangle$ term which largely cancels out its counterpart in the $\langle v_{1,\alpha}v_{1,\beta} \rangle$ term.

In the case where the difference between the like- and unlike-sign pair correlators truly results from the charge separation due to a $P$-odd domain in the medium, we expect that the two particles from the same domain are close to each other in the rapidity space. In other words, there should be a dependence of the signal on the separation of the two particles. In Fig. 5, we show the correlator as a function of pseudo-rapidity separation for 20% - 70% collisions. While the unlike-sign correlator is always close to zero, the like-sign correlator shows a clear trend: the correlator has the largest magnitude when the two particles are close to each other, and approaches zero when they are further apart. This dependence on the pseudo-rapidity separation supports the picture of the local parity violation.

When the two particles have a small $p_T$ gap (e.g. below 50 MeV/c), the correlator may be dominated by quantum interference (HBT) or Coulomb effects. To study this type of systematics, we show in Fig. 6 the correlator as a function of transverse momentum separation for 20% - 70% collisions. At small $p_T$ gap, both like- and unlike-sign pair correlators show a structure possibly induced by HBT or Coulomb effects. Above a $p_T$ gap $\sim$ 200 MeV/c, the unlike-sign correlator is consistent with zero, and the like-sign correlator is sizably negative, excluding HBT or Coulomb effects as possible explanations for the signal. Furthermore, the smaller difference between the like- and unlike-sign correlator at a small $p_T$ gap compared with the sizable difference at a higher $p_T$ gap means that HBT or Coulomb effects would reduce the integrated signal instead of increasing it. There are no specific theoretical predictions on this dependence for the parity violation effect, though naively one would expect that the signal should not extend to large values of $p_T$ gap. Our measurement at high $p_T$ gap seems to indicate that the like-sign correlator is approaching zero, but the statistical errors are too large to be conclusive.
4. Conclusion

To study the possible local $\mathcal{P}$-violation effects in heavy-ion collisions, we have employed the first-order event plane from STAR ZDC-SMDs to calculate the three-particle correlator which is sensitive to the predicted charge separation with respect to the reaction plane. The correlator thus measured is consistent with that estimated with a third particle from TPC, indicating that the reaction-plane independent non-flow and non-parity correlations largely cancel out. Qualitatively the results agree with the gross features of the theoretical predictions for $\mathcal{P}$-violation in heavy-ion collisions with charge separation across the reaction plane suppressed by the medium opacity. We have demonstrated that the global $\mathcal{P}$-violation term and the directed flow have negligible contributions to the correlator. The dependence of the correlator on the pseudo-rapidity separation of the two particles supports the picture of local parity violation. We have checked the $p_T$-gap dependence of the correlator, and found that HBT or Coulomb effects reduce the signal instead of increasing it.

Acknowledgments

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