Systematic studies of charge-dependent azimuthal correlation in pPb and PbPb collisions at the LHC

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Studies of charge-dependent azimuthal correlations for same- and opposite-sign particle pairs are presented in PbPb collisions at 5.02 TeV and pPb colisions at 5.02 and 8.16 TeV, with the CMS experiment at the LHC. The azimuthal correlations are evaluated with respect to the second- and also higher-order event planes, as a function of particle pseudorapidity and transverse momentum, and event multiplicity. By employing an event-shape engineering technique, the dependence of correlations on azimuthal anisotropy flow is investigated. Results presented provide new insights to the origin of observed charge-dependent azimuthal correlations, and have important implications to the search for the chiral magnetic effect in heavy ion collisions.

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1. Introduction

A metastable gluon field with nontrivial topological fluctuations may cause parity and charge conjugation parity violating effects in local space and time. In relativistic heavy ion collisions, this fluctuation is dominated by the sphaleron transition in the Quantum Chromodynamics (QCD) vacuum [1, 2, 3, 4]. The interaction between the chiral quarks and these gluon field can lead to a chirality imbalance, μ_5, where number of left- and right-handed particles are not equal. Therefore, the extremely strong magnetic field that can be produced by heavy ion collisions, will induce an electric current along or opposite to the direction of magnetic field, in which final-state charged-particles would be separated with respect to the reaction plane. This phenomenon is known as the "chiral magnetic effect" (CME).

The CME has been extensively studied both experimentally and theoretically. The measurement was firstly done by the STAR Collaboration and later ALICE Collaboration [5, 6, 7, 8, 9] using a charge-dependent three-particle azimuthal correlator with respect to the reaction plane. The results are found to be consistent with the CME expectations. However, non-negligible backgrounds related to the elliptic flow, momentum conservation, local charge conservation, and other short-range correlations have been identified, which have been found to be qualitatively consistent with the experimental data [10, 11, 12, 13, 14, 15]. One of the proposed background mechanisms is related to the local charge conservation coupled with an anisotropic flow at the freezeout surface, where short-range correlation caused by jets or resonance decays that coupled with a strong elliptic flow can play an important role in the charge-dependent three-particle correlator, γ [11, 14, 15]. However, this speculation has never been directly confirmed using the experimental data.

Recently, the CMS experiment published a new measurement of studying the CME with γ-correlator in high-multiplicity pPb and peripheral PbPb collisions, where similar signal has been observed between pPb and PbPb systems [16, 17]. Because of the small magnetic field and its decorrelation to the second-order event plane in pA collisions [16], the CME is not expected to be observed in such small systems. Therefore, this data poses a challenge to the interpretation of the CME in AA collisions. It has been suggested that the lifetime of the strong magnetic field will not survive long enough at LHC energies in order to have CME to be present even in AA collisions. However, assuming there is no CME present at LHC energies, the CMS data still cannot be explained from a pure background model if the background is dominated by a flow only scenario, $\sim v_2/N$, where N is charged-particle multiplicity. Therefore, understanding the background related to this γ correlator is also extremely important for searching the CME.

A very recent analysis of constraining the CME background has been carried by the CMS Collaboration [17]. Along with a new proposal of constraining the background, this result provides an upper limit on the CME fraction with respect to the γ correlator, using an event shape engineering (ESE) technique in both pPb and PbPb collisions. As suspected in Ref. [11, 14, 15], the local charge conservation coupled with elliptic flow can account for most of the charge-dependent correlation in γ correlator. Following these studies, it is natural to expect the same mechanism would happen if the higher-order harmonic is measured. Therefore, the CMS collaboration has proposed a new correlator, $\gamma_{123} \equiv \left\langle \cos\left(\phi_\alpha + 2\phi_\beta - 3\Psi_3\right)\right\rangle$, which is expected to be a CME free correlator because of the decorrelation between the event planes Ψ_2 and Ψ_3 [18]. However, this can be extremely useful for testing whether the dominated source of background is related to the local charge conservation and anisotropic flow, because one would expect, $\Delta\gamma_{112}/v_2\Delta\delta \approx \Delta\gamma_{123}/v_3\Delta\delta$, where Δ represents the difference between same and opposite sign pairs, $\delta \equiv \left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle$ is a two-particle correlation between the α and β particles and γ_{112} is the same as the conventional γ-correlator (hereafter γ_{112}- and γ-correlator are used intermittently). The advantage of using this correlator is that it provides an independent constrain on the background mechanism without involving any theoretical models. Furthermore, not only the background mechanism has been explored, an upper limit on the v_2-independent component fraction with respect to the γ_{112} correlator that is directly related to the CME, has been set for both pPb and PbPb collisions using an ESE method. Instead of changing the centrality or multiplicity, the ESE method provides an independent handle on the initial geometry of the collisions, which is proportional to the elliptic flow, so that the γ_{112} correlator can be explicitly studied as a function of v_2 without changing the magnetic field [19, 17, 9]. This talk focused mainly on the new results that published from CMS Collaboration in Ref. [17], while details of the CMS detector can be found in Ref. [20].

2. Results

2.1 Higher-harmonic correlator

In Fig. 1, the difference between opposite sign (OS) and same sign (SS) three-particle correlators $\Delta\gamma_{112}$ (upper) and $\Delta\gamma_{123}$ (middle), and two-particle correlator, $\Delta\delta$ (lower) are shown as a function of $|\Delta\eta|$ (left), $|\Delta p_T|$ (middle), and $\overline{p}_T$ (right), for multiplicity range $185 \leq N_{trk}^{offline} < 250$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and PbPb collisions at 5.02 TeV. For pPb collisions, results that are obtained with particle c from the Pb-going direction and the p-going direction are shown separately. It is shown that the $\Delta\gamma_{123}$ and $\Delta\delta$ correlator are both charge dependent at similar $|\Delta\eta|$, $|\Delta p_T|$, and $\overline{p}_T$ range as it is found in $\Delta\gamma_{112}$, where no charge separation is expected for the $\Delta\gamma_{123}$ correlator. Furthermore, the two-particle correlator, $\Delta\delta$, in pPb collisions are found to have a larger magnitude than that in PbPb collisions, except the high $\overline{p}_T$ region.

In order to explore the multiplicity dependence of the charge-dependent correlators, the SS and OS three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower), averaged over $|\Delta\eta| < 1.6$ as a function of $N_{trk}^{offline}$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and PbPb collisions at 5.02 TeV, are shown in Fig. 2. The published results from pPb collisions at 5.02 TeV are also shown [16]. In pPb collisions, the particle c for three-particle correlators is taken from the Pb-going direction of the HF detectors. The average over $|\Delta\eta| < 1.6$ is weighted by the density of particle pairs in $|\Delta\eta|$. Hereafter, all figures that averaged over $|\Delta\eta| < 1.6$ are weighted similarly.

From 5.02 TeV to 8.16 TeV, the SS and OS three-particle correlator, γ_{112}, in pPb collisions have been found to be the same within uncertainties and both agree with results from PbPb collisions, which indicates the γ_{112} correlator is mostly dominated by background correlation at both collision energies and systems. On the other hand, both OS and SS of γ_{123} in pPb collisions are different than that in PbPb collisions. For two-particle correlator, δ, the SS shows similar magnitude between pPb and PbPb collisions, while OS shows different values.

However, the individual SS and OS correlators also have charge-independent correlations (e.g., momentum conservation) and the difference in OS and SS should largely cancel out those effects. In Fig. 3, the difference between OS and SS three-particle correlators, γ_{112} (upper) and γ_{123} (middle),

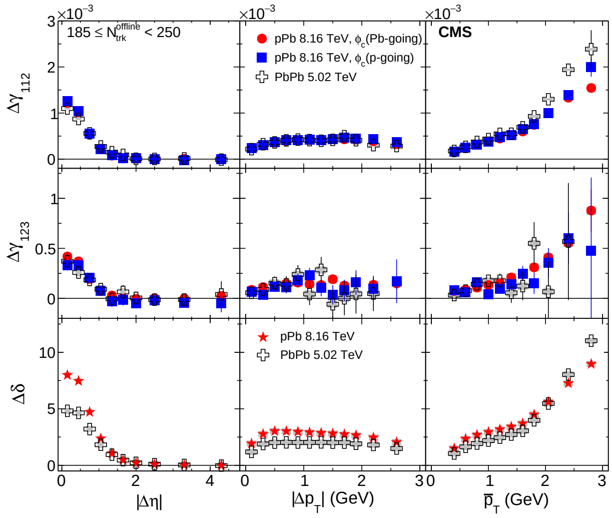

Figure 1: The difference of the OS and SS three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower) as functions of $|\Delta\eta|$ (left), $|\Delta p_{\mathrm{T}}|$ (middle), and $\overline{p}_{\mathrm{T}}$ (right) for $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV and PbPb collisions at 5.02 TeV [17]. The $\Delta\delta$ correlator is denoted by a different marker for pPb collisions. The pPb results are obtained with particle c from Pb- and p-going sides separately. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

and two-particle correlators, δ (lower), averaged over $|\Delta\eta| < 1.6$ as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV and PbPb collisions at 5.02 TeV, are shown. The results in terms of γ_{112} from 5.02 TeV pPb collisions are also shown for comparison [16]. Note that the $\Delta\delta$ is shown very differently between pPb and PbPb collisions, with pPb collisions a larger magnitude. Given the v_2, however, is larger in PbPb than in pPb collisions at the same multiplicity, a similar value between pPb and PbPb collisions in terms of the $\Delta\gamma_{112}$ can be explained by the difference in v_2 and $\Delta\delta$ correlator, which is expected from the background mechanism of local charge conservation coupled with the anisotropy flow.

To test if the γ_{112} is entirely from background, the ratios of $\Delta\gamma_{112}/v_2\Delta\delta$ and $\Delta\gamma_{123}/v_3\Delta\delta$ are compared in Fig. 4 as a function of $|\Delta\eta|$ (left), $|\Delta p_{\mathrm{T}}|$ (middle), and $\overline{p}_{\mathrm{T}}$ (right) for $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV (upper) and PbPb collisions at 5.02 TeV (lower). These ratios are expected to be harmonic independent to the first order as they are related to the particle productions and detector acceptance [17, 14]. In Fig. 4, these ratios are found to be the same for both harmonic order n=2 and 3, for both collision systems, and for all the measured differential observables, which indicates again a pure background scenario for the γ_{112} correlator. In addition, these ratios are almost invariant for different multiplicity ranges [17], which would have been different if the correlation is dominated by the event plane correlation between the second- and the third-order [18]. The measurement of this ratio, usually regarded as κ, has been constrained for the background only scenario in a data-driven way. For future CME searches, this has provided a new experimental approach to constrain the κ parameter, which can be used to estimate the background contribution together with a measurement of v_2 and δ correlator.

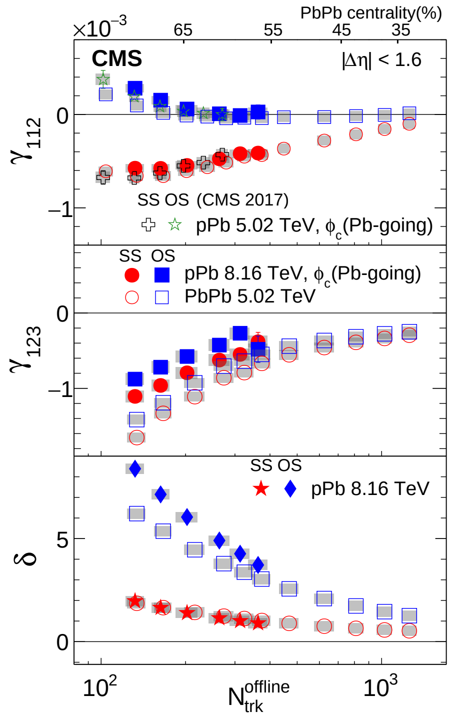

Figure 2: The SS and OS three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower), averaged over $|\Delta\eta| < 1.6$ as a function of $N_{\rm trk}^{\rm offline}$ in pPb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV and PbPb collisions at 5.02 TeV [17]. The SS and OS two-particle correlators are denoted by different markers for pPb collisions. The results of γ_{112} for pPb collisions at 5.02 TeV from CMS Collaboration (CMS 2017 [16]), are also shown for comparison. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

2.2 Event shape engineering (ESE)

It has been shown in the previous section that the γ_{112} is consistent with a pure background scenario, where the background has been found to be an interplay between local charge conservation and the anisotropy flow. However, the v_2-independent component, which is believed to be related to the CME, still remains unknown. Using an ESE technique, events in the same multiplicity or centrality range with different average v_2 values can be selected without changing the magnetic field, a consequence of the initial-state fluctuation. As a result, the charge-dependent correlator $\Delta\gamma_{112}$ can be studied explicitly as a function of v_2, and its intercept when $v_2 = 0$.

In Fig. 6, the ratios between $\Delta\gamma_{112}$ and $\Delta\delta$ correlators, averaged over $|\Delta\eta| < 1.6$ as a function of v_2 (evaluated as the average v_2 in each q_2 event class), for different centrality classes in PbPb collisions at $\sqrt{s_{\rm NN}}$=5.02 TeV, are shown. The $\Delta\gamma_{112}$ and $\Delta\delta$ as a function of v_2 separately can be found in Ref. [17]. After taking the ratio, the v_2 dependence of the $\Delta\delta$ correlator is expected to be removed, and the intercepts can be interpreted as the v_2-independent component that is related to the CME (scaled by $1/\Delta\delta$). As one can see from Fig. 6, this ratio is linear as a function of v_2 and the intercepts are found to be consistent with zero, which is expected from a pure background scenario without any CME signal. Similar results have been found in pPb collisions [17].

In order to quantify the intercepts and the possible remaining CME fraction in terms of the

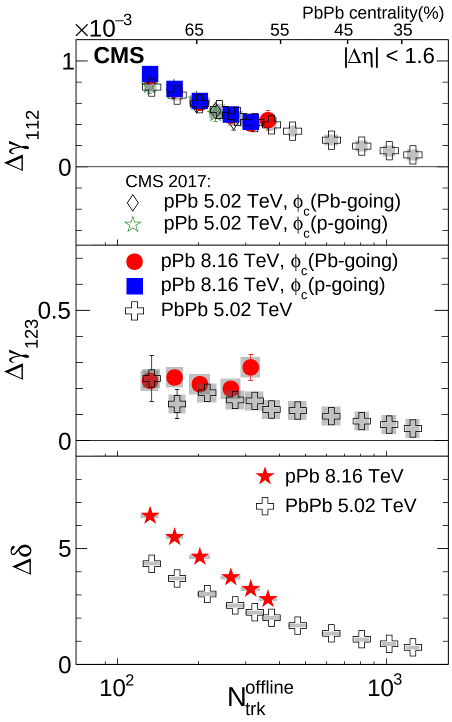

Figure 3: The difference of the OS and SS three-particle correlators, γ_{112} (upper) and γ_{123} (middle), and two-particle correlator, δ (lower), averaged over $|\Delta\eta| < 1.6$ as a function of $N_{\rm trk}^{\rm offline}$ in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV and PbPb collisions at 5.02 TeV [17]. The pPb results are obtained with particle c from Pb- and p-going sides separately. The $\Delta\delta$ correlator is denoted by a different marker for pPb collisions. The results of γ_{112} for pPb collisions at 5.02 TeV from CMS Collaboration (CMS 2017 [16]), are also shown for comparison. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

$\Delta\gamma_{112}$ correlator, the intercepts, $b_{\rm norm}$, from Fig. 6 (left) and the upper limits at 95% confidence level (CL) on the v_2-independent fraction, $f_{\rm norm}$ (right), are shown as a function of multiplicity in pPb and PbPb collisions. After combining all the measured multiplicities and centralities, the upper limit at 95% CL is found to be 6.6% and 3.8% for pPb and PbPb collisions, respectively. Note that the dominant uncertainty comes from the systematics instead of statistics, where more data is not going to improve the precision of this measurement.

A similar study has been recently done by the ALICE Collaboration [9], where details of extracting the v_2-independent component are slightly different. Because of the finite resolution of the v_2 measurement, the expected CME signal that can be experimentally measured also depends on the value of v_2. However, this correlation is only accessible via model-dependent simulations, and the upper limits that extracted from CMS Collaboration [17] may increase by ~20% depending on specific models with different initial-state fluctuations, which would still be at a few % level. Therefore, the precision measurement of the charge-dependent three-particle azimuthal correlations in pPb and PbPb collisions are consistent with a pure background scenario, posing a constrain to the possible CME signal at LHC energies.

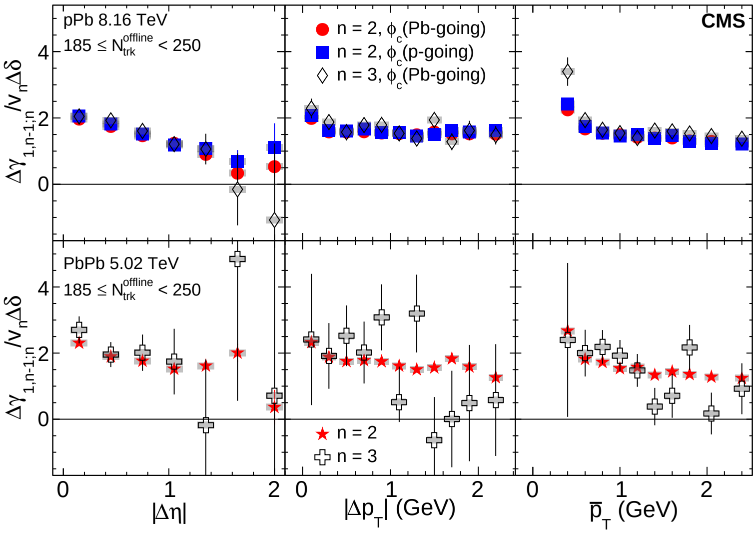

Figure 4: The ratio of $\Delta\gamma_{112}$ and $\Delta\gamma_{123}$ to the product of v_n and δ, as functions of $|\Delta\eta|$ (left), $|\Delta p_T|$ (middle), and $\overline{p}_T$ (right) for $185 \le N_{trk}^{offline} < 250$ in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV (upper) and PbPb collisions at 5.02 TeV (lower) [17]. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

3. Summary

Charge-dependent azimuthal correlations of same- and opposite-sign (SS and OS) pairs with respect to the second- and third-order event planes have been studied in pPb collisions at $\sqrt{s_{NN}}$= 8.16 TeV and PbPb collisions at 5.02 TeV by the CMS experiment at the LHC. With the independent constrain from the charge-dependent three-particle correlator with respect to the third-order event plane, it has been found that the background mechanism is consistent with local charge conservation coupled with the anisotropy flow. In addition, the ratio, divided the OS and SS difference of the three-particle correlator by the product of v_n harmonic of the corresponding order and the difference of the two-particle correlator, is experimentally constrained at the value around 2 at LHC energies, which provides a new experimental approach to the understanding of background contribution in terms of the charge-dependent correlators. Moreover, using an event shape engineering technique, the upper limit on the v_2-independent fraction that is related to the CME, has been found to be 6.6% and 3.8% for pPb and PbPb collisions, respectively, at 95% confidence level after combining all the measured multiplicity and centrality ranges. Therefore, this measurement not only provides a constrain on the magnitude of the possible CME signal at LHC energies, but also a new baseline and experimental approach of searching the CME signal for future attempts.

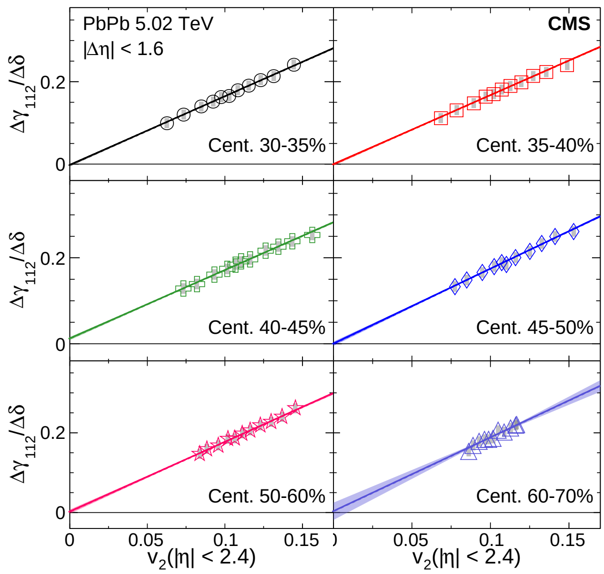

Figure 5: The ratio between the difference of the OS and SS three-particle correlators and the difference of OS and SS in δ correlators, $\Delta\gamma_{112}/\Delta\delta$, averaged over $|\Delta\eta| < 1.6$ as a function of v_2 evaluated in each q_2 class, for different centrality classes in PbPb collisions at $\sqrt{s_{\rm NN}}$=5.02 TeV [17]. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively. A one standard deviation uncertainty from the fit is also shown.

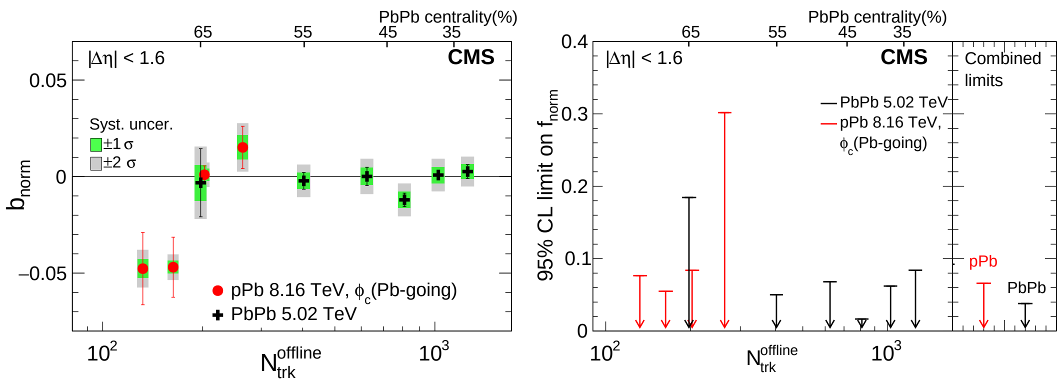

Figure 6: Extracted intercept parameter $b_{\rm norm}$ (left) and corresponding upper limit of the fraction of v_2-independent γ_{112} correlator component (right), averaged over $|\Delta\eta| < 1.6$, as a function of $N_{\rm trk}^{\rm offline}$ in pPb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV and PbPb collisions at 5.02 TeV [17]. Statistical and systematic uncertainties are indicated by the error bars and shaded regions in the top panel, respectively.

References

[1] T. D. Lee, *A theory of spontaneous T violation*, *Phys. Rev. D* **8** (1973) 1226.

[2] T. D. Lee and G. C. Wick, *Vacuum stability and vacuum excitation in a spin-0 field theory*, *Phys. Rev. D* **9** (1974) 2291.

[3] P. D. Morley and I. A. Schmidt, *Strong p, cp, t violations in heavy-ion collisions*, *Z. Phys. C* **26** (1985) 627.

[4] D. Kharzeev, R. D. Pisarski and M. H. G. Tytgat, *Possibility of spontaneous parity violation in hot QCD*, *Phys. Rev. Lett.* **81** (1998) 512, [hep-ph/9804221].

[5] STAR collaboration, B. I. Abelev et al., *Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation*, *Phys. Rev. Lett.* **103** (2009) 251601, [0909.1739].

[6] STAR collaboration, L. Adamczyk et al., *Beam-Energy Dependence of Charge Separation along the Magnetic Field in Au+Au Collisions at RHIC*, *Phys. Rev. Lett.* **113** (2014) 052302, [1404.1433].

[7] STAR collaboration, L. Adamczyk et al., *Fluctuations of charge separation perpendicular to the event plane and local parity violation in* $\sqrt{s_{NN}}$ *= 200 GeV Au+Au collisions at the BNL Relativistic Heavy Ion Collider*, *Phys. Rev. C* **88** (2013) 064911, [1302.3802].

[8] ALICE collaboration, B. Abelev et al., *Charge separation relative to the reaction plane in Pb-Pb collisions at* $\sqrt{s_{NN}}$ *= 2.76 TeV*, *Phys. Rev. Lett.* **110** (2013) 012301, [1207.0900].

[9] ALICE collaboration, S. Acharya et al., *Constraining the magnitude of the Chiral Magnetic Effect with Event Shape Engineering in Pb-Pb collisions at* $\sqrt{s_{NN}}$ *= 2.76 TeV*, 1709.04723.

[10] D. E. Kharzeev, J. Liao, S. A. Voloshin and G. Wang, *Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report*, *Prog. Part. Nucl. Phys.* **88** (2016) 1, [1511.04050].

[11] S. Schlichting and S. Pratt, *Charge conservation at energies available at the BNL Relativistic Heavy Ion Collider and contributions to local parity violation observables*, *Phys. Rev. C* **83** (2011) 014913, [1009.4283].

[12] F. Wang, *Effects of cluster particle correlations on local parity violation observables*, *Phys. Rev. C* **81** (2010) 064902, [0911.1482].

[13] F. Wang and J. Zhao, *Challenges in flow background removal in search for the chiral magnetic effect*, *Phys. Rev. C* **95** (2017) 051901, [1608.06610].

[14] A. Bzdak, V. Koch and J. Liao, *Charge-Dependent Correlations in Relativistic Heavy Ion Collisions and the Chiral Magnetic Effect*, Lect. Notes Phys. **871** (2013) 503–536, [1207.7327].

[15] A. Bzdak, V. Koch and J. Liao, *Azimuthal correlations from transverse momentum conservation and possible local parity violation*, *Phys. Rev. C* **83** (2011) 014905, [1008.4919].

[16] CMS collaboration, V. Khachatryan et al., *Observation of charge-dependent azimuthal correlations in pPb collisions and its implication for the search for the chiral magnetic effect*, *Phys. Rev. Lett.* **118** (2017) 122301, [1610.00263].

[17] CMS collaboration, A. M. Sirunyan et al., *Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the LHC*, 1708.01602.

[18] ATLAS collaboration, G. Aad et al., *Measurement of event-plane correlations in* $\sqrt{s_{NN}}$ *= 2.76 TeV lead-lead collisions with the ATLAS detector*, *Phys. Rev. C* **90** (2014) 024905, [1403.0489].

PoS(CPOD2017)045

[19] F. Wen, L. Wen and G. Wang, *Procedure for removing flow backgrounds from the charge-separation observable perpendicular to the reaction plane in heavy-ion collisions*, 1608.03205.

[20] CMS collaboration, S. Chatrchyan et al., *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004.