Observation of Charge-Dependent Azimuthal Correlations in *p*-Pb Collisions and Its Implication for the Search for the Chiral Magnetic Effect

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Charge-dependent azimuthal particle correlations with respect to the second-order event plane in *p*-Pb and PbPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV have been studied with the CMS experiment at the LHC. The measurement is performed with a three-particle correlation technique, using two particles with the same or opposite charge within the pseudorapidity range $|\eta| < 2.4$, and a third particle measured in the hadron forward calorimeters ($4.4 < |\eta| < 5$). The observed differences between the same and opposite sign correlations, as functions of multiplicity and η gap between the two charged particles, are of similar magnitude in *p*-Pb and PbPb collisions at the same multiplicities. These results pose a challenge for the interpretation of charge-dependent azimuthal correlations in heavy ion collisions in terms of the chiral magnetic effect.

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In relativistic heavy ion collisions, metastable domains of gluon fields may form with nontrivial topological configurations [1–4]. The interaction of quarks with these gluon fields will lead to an imbalance in left- and right-handed quarks, which violates local parity (P) symmetry [3,4]. In the presence of a strong magnetic field in a noncentral nucleus-nucleus (AA) collision, this chirality imbalance leads to an electric current perpendicular to the reaction plane, resulting in a final-state charge separation phenomenon, known as the chiral magnetic effect (CME) [5]. Attempts to measure this charge separation in heavy ion collisions were made by the STAR experiment at RHIC [6–10] and the ALICE experiment at the LHC [11]. In these measurements, a charge dependence of azimuthal correlations with respect to the reaction plane was observed, which is qualitatively consistent with the expectation of a charge separation from the CME.

The charge separation can be characterized by the P-odd sine term (a_1) in a Fourier decomposition of the particle azimuthal distribution [12]:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n (v_n \cos[n(\phi - \Psi_{\mathrm{RP}})] + a_n \sin[n(\phi - \Psi_{\mathrm{RP}})]), \tag{1}$$

where $\phi - \Psi_{\mathrm{RP}}$ represents the particle azimuthal angle with respect to the reaction plane angle Ψ_{RP} (determined by the impact parameter and beam axis), v_n and a_n denote the coefficients of P-even and P-odd Fourier terms, respectively. Although the reaction plane is not an experimental observable, it can be approximated by the second-order event plane, Ψ_{EP}, determined by the direction of the beam and the maximal particle density in the elliptic azimuthal anisotropy. An azimuthal correlator proposed to explore the first coefficient, a_1, of the P-odd Fourier terms characterizing the charge separation [12] is

$$\begin{aligned}\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{EP}})\rangle &= \langle\cos(\phi_\alpha - \Psi_{\mathrm{EP}})\cos(\phi_\beta - \Psi_{\mathrm{EP}})\rangle \\ &\quad - \langle\sin(\phi_\alpha - \Psi_{\mathrm{EP}})\sin(\phi_\beta - \Psi_{\mathrm{EP}})\rangle.\end{aligned} \tag{2}$$

Here, α and β denote particles with the same or opposite charge sign and the brackets reflect an averaging over particles and events. Assuming particles α, β are uncorrelated except for their individual correlations with respect to the event plane, the first term on the right-hand side of Eq. (2) becomes $\langle v_{1,\alpha} v_{1,\beta}\rangle$, which is generally small and independent of charge [7], while the second term is sensitive to charge separation and can be expressed as $\langle a_{1,\alpha} a_{1,\beta}\rangle$, which can be measured.

The observation of the CME in heavy ion collisions remains inconclusive because of several identified sources of background correlations that can account for part or all of the observed charge-dependent azimuthal correlations [13–15]. For example, the effect of local charge conservation, coupled with the anisotropic emission of particles (v_2), can generate an effect resembling charge separation with respect to the reaction plane [15]. The charge-dependent azimuthal correlation signals observed in the data can be qualitatively described by models that do not include CME, such as the AMPT [16] and EPOS LHC [17] models. A significant amount of recent experimental and

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theoretical effort is directed toward quantifying possible mechanisms, including the CME, that can lead to charge-dependent azimuthal correlations [18].

This Letter presents the first application of charge-dependent azimuthal correlation analysis with respect to the event plane in proton-nucleus collisions, using p-Pb data collected with the CMS detector at the LHC at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. High-multiplicity pp and p-Pb collisions have been shown to generate large final-state azimuthal anisotropies, comparable to those in AA collisions [19–32]. However, the CME contribution to any charge-dependent signal is expected to be small in a high-multiplicity p-Pb collision, as the proton likely intersects the Pb nucleus at a small impact parameter. Consequently, the magnetic field in the proton-nucleus overlap region is expected to be smaller than in peripheral PbPb collisions at similar multiplicities. Furthermore, based on Monte Carlo (MC) Glauber calculations [33], the angle between the magnetic field direction and the event plane of elliptic anisotropy is randomly distributed in p-Pb collisions, contrary to the situation for PbPb collisions. With a reduced magnetic field strength and a random field orientation, the CME contribution to any charge-dependent signal is expected to be small. The high-multiplicity events in p-Pb collisions exhibit collective effects and bulk properties similar to those found in AA collisions [29,31,34] but possess very different strengths and configurations of the initial magnetic field. Thus, they can provide a new way to explore the possible CME and local strong parity violation. With the implementation of a high-multiplicity trigger, the p-Pb data sample gives access to multiplicities comparable to those in peripheral PbPb collisions (e.g., ~55% centrality, where centrality is defined as the fraction of the total inelastic cross section, with 0% denoting the most central collisions), allowing for a direct comparison of the two systems with very different CME contributions in the overlap zone. The measurement is presented in different charge combinations as functions of event multiplicity and pseudorapidity (η) difference of correlated particles. In p-Pb collisions, the particle correlations with respect to the event planes that are obtained using particles with $4.4 < |\eta| < 5$ from the p- and Pb-going beam direction, are also explored.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are four primary subdetectors including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end cap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For charged particles with transverse momentum $1 < p_{\mathrm{T}} < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [35]. Iron and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the range $2.9 < |\eta| < 5.2$. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [36].

The p-Pb data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, collected in 2013 at the LHC, correspond to an integrated luminosity of 35 nb^{-1}. The beam energies are 4 TeV for the protons and 1.58 TeV per nucleon for the lead nuclei. A subset of peripheral PbPb data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV collected in 2015 (30%–80% centrality) is also used. The PbPb data were reprocessed using the same reconstruction algorithm as the p-Pb data, in order to directly compare the two systems at similar multiplicities. The event reconstruction, event selections, and the triggers, including the dedicated triggers to collect a large sample of high-multiplicity p-Pb events, are identical to those used in previous CMS particle correlation measurements [19,29]. In the offline analysis of p-Pb (PbPb) collisions, hadronic events are selected by requiring the presence of at least one (three) energy deposit(s) greater than 3 GeV in each of the two HF calorimeters. Events are also required to contain a primary vertex within 15 cm of the nominal interaction point along the beam axis and 0.15 cm in the transverse direction. In the p-Pb data sample, there is a 3% probability to have at least one additional interaction in the same bunch crossing (pileup). The procedure used to reject pileup events in p-Pb collisions yields a purity of 99.8% for single p-Pb collision events and is described in Ref. [29]. The pileup in PbPb data is negligible.

Primary tracks, i.e., tracks that originate at the primary vertex and satisfy the high-purity criteria of Ref. [35], are used to define the event charged-particle multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}}$) and to perform correlation measurements. In addition, the impact parameter significance of the track with respect to the primary vertex in the direction along the beam axis, $d_z/\sigma(d_z)$ is required to be less than 3, as is the corresponding impact parameter significance in the transverse plane, $d_T/\sigma(d_T)$. The relative uncertainty in p_{T}, $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}$, must be less than 10%. Each track is also required to leave at least one hit in one of the three layers of the pixel tracker. To ensure high tracking efficiency, only tracks with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.3$ GeV are used in this analysis.

The p-Pb and PbPb data are compared in classes of $N_{\mathrm{trk}}^{\mathrm{offline}}$, where primary tracks with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4$ GeV are counted. To compare with results from other experiments, the PbPb data are also analyzed based on centrality classes for the 30%–80% centrality range. The average values of multiplicity, before and after correcting for detector and algorithm inefficiencies, in each multiplicity class of p-Pb and PbPb data, can be found in Ref. [29].

Without directly reconstructing the event plane, the expression shown in Eq. (2) can be alternatively evaluated using a three-particle correlator with respect to a third particle [6,7], $\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c}$, where $v_{2,c}$ corresponds to the elliptic flow of the particle c. The three-particle correlator is measured via the scalar product method of Q vectors [7,37]. The particles α and β are taken from the tracker with $|\eta| < 2.4$ and $0.3 < p_T < 3$ GeV, and are corrected for tracking efficiency to account for reconstruction effects. The particle c is measured by using the tower energies in the HF calorimeters with $4.4 < |\eta| < 5.0$. This choice of η range for HF towers imposes an η gap of at least 2 units with respect to particles α and β from the tracker, to minimize possible short-range correlations. To account for any occupancy effect of the HF detectors resulting from the large granularities in η and ϕ, each tower is weighted by its E_T value when calculating the Q vector. The $v_{2,c}$ is obtained following the standard scalar-product method [6,7], by correlating the Q vectors from the tracker region at midrapidity and the two HF detectors at forward rapidity. The three-particle correlator is evaluated for particles α and β carrying same sign (SS) and opposite sign (OS), as a function of pseudorapidity difference $|\Delta\eta|$ ($\equiv |\eta_\alpha - \eta_\beta|$). The SS combinations, $(+,+)$ and $(-,-)$, give consistent results within statistical uncertainty and are therefore combined. For p-Pb collisions, the three-particle correlator is also measured with particle c from HF+ and HF−, corresponding to the p- and Pb-going direction, respectively. For symmetric PbPb collisions, the results from HF+ and HF− are consistent with each other within statistical uncertainty and are therefore averaged. The effect of the nonuniform detector acceptance is found to be negligible by evaluating the cumulants of Q-vector products [38].

The absolute systematic uncertainty of the three-particle correlator has been studied. Varying the $d_z/\sigma(d_z)$ and $d_T/\sigma(d_T)$ from less than 3 (default) to less than 2 and 5, and the $\sigma(p_T)/p_T < 10\%$ (default) to $\sigma(p_T)/p_T < 5\%$, together yield a systematic uncertainty of $\pm 1.0 \times 10^{-5}$. The longitudinal primary vertex position (V_z) has been varied, using ranges $|V_z| < 3$ cm and $3 < |V_z| < 15$ cm, where the difference with respect to the default range $|V_z| < 15$ cm is $\pm 1.0 \times 10^{-5}$, taken as the systematic uncertainty. In p-Pb collisions only, using the lower threshold of the high-multiplicity trigger yields a systematic uncertainty of $\pm 3.0 \times 10^{-5}$, which accounts for the possible trigger bias from the inefficiency of the default trigger around the threshold. A final test of the analysis procedures is done by comparing "known" charge-dependent signals based on the EPOS event generator to those found after events are passed through a GEANT4 [39] simulation of the CMS detector response. Based on this test, a systematic uncertainty of $\pm 2.5 \times 10^{-5}$ is assigned. The tracking efficiency and acceptance of positively and negatively charged particles have been evaluated separately, and the difference has been found to be negligible. All sources of systematic uncertainty are uncorrelated and added in quadrature to obtain the total absolute systematic uncertainty. No dependence of the systematic uncertainties on the sign combination, multiplicity, or $\Delta\eta$ is found. The systematic uncertainties in our results as a function of $|\Delta\eta|$ and multiplicity are point-to-point correlated. In p-Pb collisions, the systematic uncertainty is also observed to be independent of particle c pointing to the Pb- or p-going direction, and thus is quoted to be the same for these two situations.

Measurements of the charge-dependent three-particle correlator are shown in Fig. 1 as a function of the $|\Delta\eta|$ between charged particles α and β with the same and opposite signs, in the multiplicity range $185 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 220$ for p-Pb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The p-Pb data are obtained with particle c in the Pb- and p-going sides separately. In both p-Pb and PbPb systems, a charge dependence of the three-particle correlator is observed for $|\Delta\eta|$ up to about 1.6. In this range, the SS correlators show significant negative values as $|\Delta\eta|$ decreases, while the OS correlators become positive towards $|\Delta\eta| \approx 0$. For $|\Delta\eta| > 1.6$, the SS and OS correlators converge to a common positive value, which is weakly dependent on $|\Delta\eta|$ up to about 4.8 units. Similar $|\Delta\eta|$ dependence of the three-particle correlator has been reported at $\sqrt{s_{\mathrm{NN}}} = 0.2$ [6] and 2.76 TeV [11], measured up to $|\Delta\eta| \approx 1.6$. In p-Pb collisions, three-particle correlators obtained with particle c from the p-going side are shifted toward more positive values than those from the Pb-going side by approximately the same amount for both the SS and OS pairs. The Pb-going side results for the p-Pb collisions are of similar magnitude as the results for PbPb collisions. The common shift of SS and OS correlators between the p- and Pb-going side reference (c) particle, may be related to sources of correlations that are

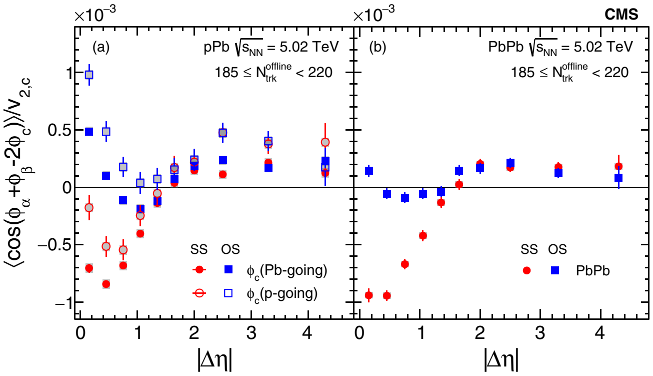

FIG. 1. The same and opposite sign three-particle correlator as a function of $|\Delta\eta| \equiv |\eta_\alpha - \eta_\beta|$ for $185 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 220$ in (a) p-Pb and (b) PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The p-Pb results obtained with particle c in Pb-going (solid markers) and p-going (open markers) sides are shown separately. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

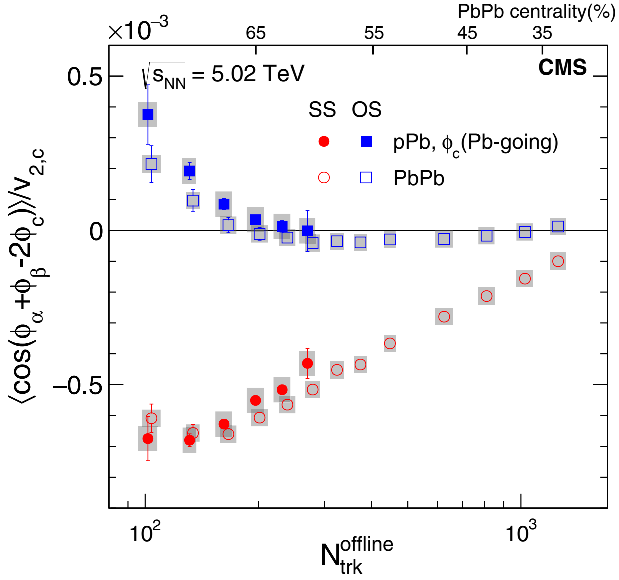

FIG. 2. The same sign and opposite sign three-particle correlator averaged over $|\eta_\alpha - \eta_\beta| < 1.6$ as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in p-Pb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are shown. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

charge-independent, such as directed flow and the momentum conservation effect, the latter being sensitive to the difference in multiplicity between p- and Pb-going directions.

To explore the multiplicity or centrality dependence of the three-particle correlator, an average of the results in Fig. 1 over $|\Delta\eta| < 1.6$ (charge-dependent region) is taken, where the average is weighted by the number of particle pairs in each $|\Delta\eta|$ range. The resulting $|\Delta\eta|$-averaged three-particle correlators are shown in Fig. 2 as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ for p-Pb (particle c from the Pb-going side) and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Up to $N_{\mathrm{trk}}^{\mathrm{offline}} = 300$, the p-Pb and PbPb results are measured in the same $N_{\mathrm{trk}}^{\mathrm{offline}}$ ranges. The centrality scale on the top of Fig. 2 relates to the PbPb experimental results. Within uncertainties, the SS and OS correlators in p-Pb and PbPb collisions exhibit the same magnitude and trend as a function of event multiplicity. The OS correlator reaches a value close to zero for $N_{\mathrm{trk}}^{\mathrm{offline}} > 200$, while the SS correlator remains negative, but the magnitude gradually decreases as $N_{\mathrm{trk}}^{\mathrm{offline}}$ increases. Part of the observed multiplicity (or centrality) dependence is understood as a dilution effect that falls with the inverse of event multiplicity [7]. The notably similar magnitude and multiplicity dependence of the three-particle correlator observed in p-Pb collisions relative to that in PbPb collisions again indicates that the dominant contribution of the signal is not related to the CME. The results of SS and OS three-particle correlators as functions of centrality in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are also found to be consistent with the results from lower energy AA collisions [7,11].

To eliminate sources of correlations that are charge independent (e.g., directed flow, v_1) and to explore a possible charge separation effect generated by the CME, the difference of three-particle correlators between the OS and SS is shown as a function of $|\Delta\eta|$ in the multiplicity range $185 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 220$ [Fig. 3(a)] and as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ averaged over $|\Delta\eta| < 1.6$ [Fig. 3(b)] for p-Pb and

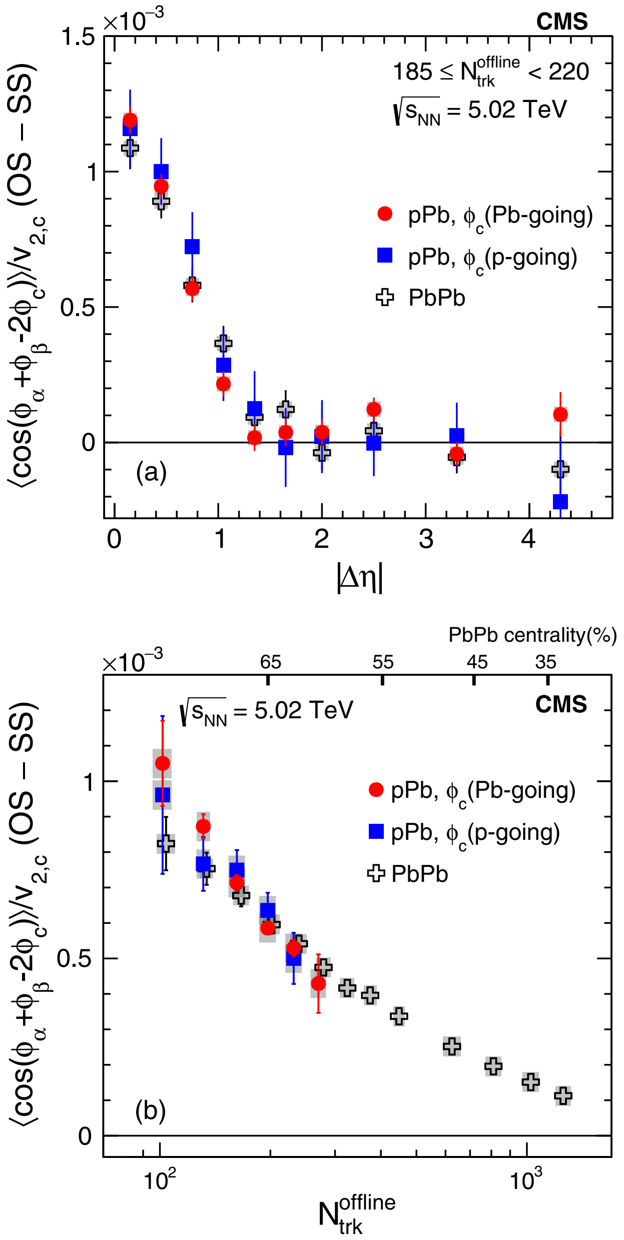

FIG. 3. The difference of the opposite sign and same sign three-particle correlators (a) as a function of $|\eta_\alpha - \eta_\beta|$ for $185 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 220$ and (b) as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$, averaged over $|\eta_\alpha - \eta_\beta| < 1.6$, in p-Pb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The p-Pb 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.

PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. After taking the difference, the p-Pb data with particle c from both the p- and Pb-going sides, and PbPb data, show nearly identical values. The charge-dependent difference is largest at $|\Delta\eta| \approx 0$ and drops to zero for $|\Delta\eta| > 1.6$, and also decreases as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$. The striking similarity in the observed charge-dependent azimuthal correlations strongly suggests a common physical origin. In PbPb collisions, it was suggested that the charge dependence of the three-particle correlator as well as its $|\Delta\eta|$ dependence are indications of the charge separation effect with respect to the event plane due to the CME [7,11]. However, as argued earlier, a strong charge separation signal from the CME is not expected in a very high-multiplicity p-Pb collision. The similarity seen between high-multiplicity p-Pb and peripheral PbPb collisions challenges the attribution of the observed charge-dependent correlations to the CME. Note that there is a hint of a slight difference between p-Pb and PbPb in the slopes of the $N_{\mathrm{trk}}^{\mathrm{offline}}$ dependence in Fig. 3(b), where the systematic uncertainties are point-to-point correlated. This difference is worth further investigation.

In summary, charge-dependent azimuthal correlations of same and opposite sign particles with respect to the second-order event plane have been measured in p-Pb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV by the CMS experiment at the LHC. The correlation is extracted via a three-particle correlator as functions of particle $|\Delta\eta|$ and charged-particle multiplicity of the event. The difference between opposite and same sign particles as functions of $|\Delta\eta|$ and multiplicity is found to agree for p-Pb and PbPb collisions, possibly indicating a common underlying mechanism that generates the observed correlation. These results challenge the CME interpretation for the observed charge-dependent azimuthal correlations in nucleus-nucleus collisions at RHIC and the LHC.

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