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As Published	10.1103/PHYSREVC.100.064908
Publisher	American Physical Society (APS)
Version	Final published version
Citable link	https://hdl.handle.net/1721.1/136077
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PHYSICAL REVIEW C **100**, 064908 (2019)

Probing the chiral magnetic wave in *p*Pb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV using charge-dependent azimuthal anisotropies

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(Received 29 August 2017; revised manuscript received 12 October 2018; published 18 December 2019)

Charge-dependent anisotropy Fourier coefficients (v_n) of particle azimuthal distributions are measured in *p*Pb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the CMS detector at the LHC. The normalized difference in the second-order anisotropy coefficients (v_2) between positively and negatively charged particles is found to depend linearly on the observed event charge asymmetry with comparable slopes for both *p*Pb and PbPb collisions over a wide range of charged particle multiplicity. In PbPb, the third-order anisotropy coefficient v_3 shows a similar linear dependence with the same slope as seen for v_2. The observed similarities between the v_2 slopes for *p*Pb and PbPb, as well as the similar slopes for v_2 and v_3 in PbPb, are compatible with expectations based on local charge conservation in the decay of clusters or resonances, and constitute a challenge to the hypothesis that, at LHC energies, the observed charge asymmetry dependence of v_2 in heavy ion collisions arises from a chiral magnetic wave.

DOI: 10.1103/PhysRevC.100.064908

I. INTRODUCTION

Observing macroscopic phenomena arising from quantum anomalies is a subject of interest for a wide range of physics communities, from magnetized relativistic matter in three-dimensional Dirac and Weyl materials [1–3] to hot plasma in the early universe or formed in relativistic heavy ion collisions [4–6]. In quantum chromodynamics, gluon fields within a localized region of space-time can form nontrivial topological configurations [7–10]. If approximate chiral symmetry is restored, the interactions of chiral quarks with these gluon fields can produce a chirality imbalance, violating the local *P* and *CP* symmetries [9,10]. This anomalous chiral effect can manifest itself as an electric current along or opposite to a strong magnetic field [11–13]. The electric charge separation produced by these currents is known as the chiral magnetic effect (CME) [11]. The chiral separation effect (CSE) is a similar process, where the separation of the chiral charges along the magnetic field will be induced by a finite density of the net electric charges [14]. The coupling of electric and chiral charge densities and currents leads to a long-wavelength collective excitation, known as the chiral magnetic wave (CMW) [14–17].

In relativistic heavy ion (*AA*) collisions, a strong magnetic field and the restoration of the approximate chiral symmetry, both necessary conditions for creating a CMW, may be present. The magnetic field is produced by the spectator protons and is, on average, perpendicular to the reaction plane defined by the impact parameter and beam directions. The propagation of the CMW leads to an electric quadrupole moment, where additional positive (negative) charges are accumulated away from (close to) the reaction plane [14]. Following a hydrodynamic evolution of the medium formed in *AA* collisions, this electric quadruple moment is expected to result in a charge-dependent variation of the second-order anisotropy coefficient (v_2) in the Fourier expansion of the final-state particle azimuthal distribution. More specifically, the v_2 coefficient will exhibit a linear dependence on the observed event charge asymmetry [14], $A_{\mathrm{ch}} \equiv (N_+ - N_-)/(N_+ + N_-)$, where N_+ and N_- denote the number of positively and negatively charged hadrons in each event,

$$v_{2,\pm} = v_{2,\pm}^{\mathrm{base}} \mp rA_{\mathrm{ch}}. \tag{1}$$

Here $v_{2,\pm}^{\mathrm{base}}$ represents the value in the absence of a charge quadrupole moment from the CMW for positively (+) and negatively (−) charged particles, and r denotes the slope parameter. In the presence of a CMW, the difference of v_2 values between positively and negatively charged particles will be proportional to A_{ch}. Similar charge-dependent effects from the CMW are not expected for the third-order anisotropy coefficient (v_3) [13].

Recent observations of the A_{ch} dependence of $v_{2,\pm}$ in *AA* collisions at RHIC at BNL and the CERN LHC are qualitatively consistent with expectations of the CMW mechanism [5,18,19]. However, the interpretation of the results remains inconclusive since alternative mechanisms have been proposed to generate charge-dependent v_2 coefficients without a CMW [20,21]. For example, it has been shown that local charge conservation (LCC) in the decay of clusters or resonances can qualitatively describe the charge-dependent v_2 data [20]. Decay particles from a lower transverse momentum (p_{T}) resonance tend to have a larger rapidity separation, resulting in

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a daughter more likely to fall outside the detector acceptance, leading to a nonzero A_{ch}. Hence, this process generates a correlation between A_{ch} and the average p_{T} of charged particles, and therefore also between A_{ch} and the v_2 coefficient, since v_2 depends on p_{T}. The LCC mechanism also applies to all higher-order anisotropy Fourier coefficients (v_n).

This paper presents measurements of the A_{ch} dependence of the $\langle p_{\mathrm{T}}\rangle$ and of the p_{T}-averaged v_n coefficients in *p*Pb and PbPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV, using data collected with the CMS experiment at the LHC. It has been shown that *pp* and *p*Pb collisions with high charged-particle multiplicities can generate large final-state azimuthal anisotropies, comparable to those in *AA* collisions at similar event multiplicities [22–35]. However, the CMW contribution to any A_{ch}-dependent v_2 signal is expected to be negligible in *p*Pb collisions: the induced magnetic field is smaller than in PbPb collisions (albeit of the same order of magnitude) and, more importantly, its correlation with the harmonic event planes is vanishingly small [6,36]. The recent observation of nearly identical charge-dependent azimuthal correlations in *p*Pb and PbPb suggested significant contamination of background sources (e.g., LCC) to any CME induced signal [6,37]. Therefore, a comparison between *p*Pb and PbPb systems and their A_{ch} dependence of the $\langle p_{\mathrm{T}}\rangle$ and the v_3 coefficient can differentiate between the CMW and LCC mechanisms. It is worth noting that a lack of experimental evidence for the CME [6,37] does not necessarily imply the absence of the CMW, as the CME requires an initial chirality imbalance from topological QCD charges (which may be too weak to be observed), whereas the CMW only requires an initial net electric charge density [14,16]. Therefore, the CME and CMW deserve independent experimental investigations.

II. THE CMS DETECTOR

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 silicon pixel and strip tracker detectors, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. For charged particles with $1 < p_{\mathrm{T}} < 10$ GeV/c 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 [38]. 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. [39].

III. EVENT AND TRACK SELECTIONS

The *p*Pb data at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV, collected in 2013 using the CMS detector, correspond to an integrated luminosity of 35 nb^{-1}. A subset of peripheral PbPb data at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV collected in 2015 (30–90% centrality, where centrality is defined as the fraction of the total inelastic cross section, with 0% denoting the most central collisions [40]), is also used. The sample is reconstructed with the same algorithm as the *p*Pb data, in order to compare directly the two systems at similar multiplicities. The event reconstruction, event selection and the trigger, 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 [6,22,32]. 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). After the procedure used to reject pileup events is applied, the remaining sample has a purity of 99.8% for single collision events [32]. 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. [38], 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 tracks with respect to the primary vertex in the beam and transverse direction is required to be less than 3. The relative uncertainty in p_{T} must be less than 10%. To ensure high tracking efficiency, only tracks with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.3$ GeV/c are used for A_{ch} and v_n measurements in this analysis. The *p*Pb and PbPb data are compared in ranges of $N_{\mathrm{trk}}^{\mathrm{offline}}$, where primary tracks with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4$ GeV/c are counted, in order to match the trigger selection criterion implemented at the HLT in *p*Pb collisions.

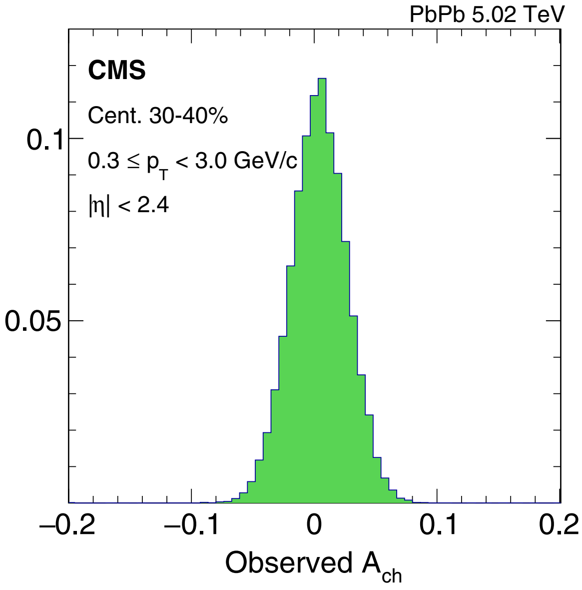

FIG. 1. The event-by-event probability distribution observed in the charge asymmetry, A_{ch}, for PbPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV within the 30–40% centrality range. The particles are selected between 0.3 and 3.0 GeV/c and having pseudorapidity $|\eta| < 2.4$.

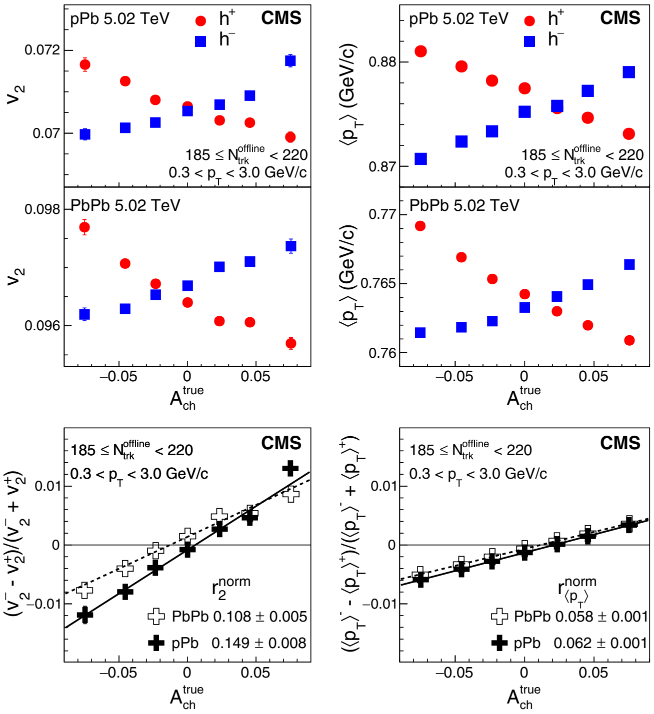

FIG. 2. The elliptic anisotropy v_2 (top left) and event-averaged $\langle p_T \rangle$ (top right) for positively (h^+) and negatively (h^-) charged particles, and their normalized differences (bottom row), as functions of $A_{\mathrm{ch}}^{\mathrm{true}}$ for the multiplicity range $185 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 220$ of *p*Pb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Statistical uncertainties are smaller than the marker size, while systematic uncertainties are not displayed.

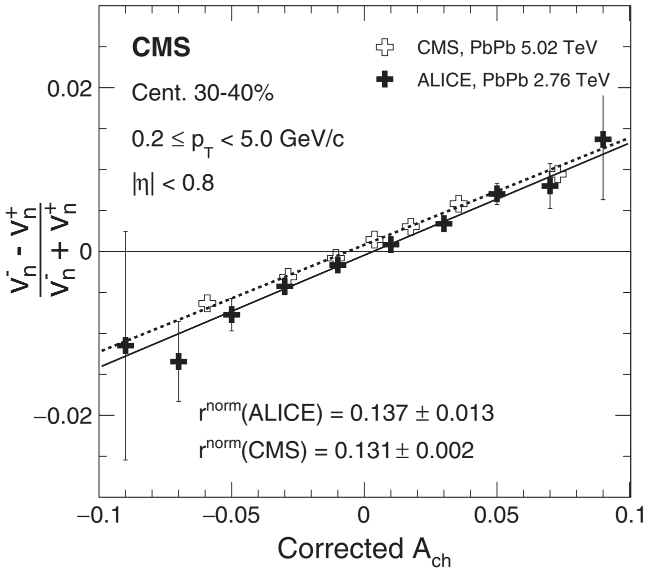

FIG. 3. The normalized difference in elliptic flow v_2 between positive- and negative-charged particles, $(v_2^- - v_2^+)/(v_2^- + v_2^+)$, as a function of charge asymmetry, is presented. The results are selected in centrality range 30–40% with particles within $|\eta| < 0.8$ and $0.2 \leqslant p_T < 5.0$ GeV, and are compared between the ALICE [19] and the CMS experiment in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV, respectively. The bars represent statistical point-by-point uncertainties.

IV. ANALYSIS TECHNIQUE

In each multiplicity or centrality class, events are further divided into several ranges of the observed event charge asymmetry $A_{\mathrm{ch}}^{\mathrm{obs}}$, calculated based on the number of positively and negatively charged particles from primary tracks. An example of the $A_{\mathrm{ch}}^{\mathrm{obs}}$ distribution for PbPb data in the 30–40% centrality range is shown in Fig. 1. Within each $A_{\mathrm{ch}}^{\mathrm{obs}}$ range, the v_n coefficients are obtained separately for tracks with positive (v_n^+) and negative (v_n^-) charge, and with $|\eta| < 2.4$ and $0.3 < p_T < 3\,\mathrm{GeV}/c$, using the two-particle cumulant method [41] with a pseudorapidity gap of at least one unit between the two particles to suppress the short-range correlations. Because of statistical limitations, the pseudorapidity gap chosen in this analysis is smaller than the value of two units typically used in other CMS correlation measurements, but results are found to be consistent between one and two units of pseudorapidity gap. Residual effects of short-range correlations may still contribute to the sum of the v_n, $v_n^- + v_n^+$, but not the difference since the effect is largely canceled out. However, this effect contributes to the *p*Pb and PbPb systems similarly [32], so it has little impact on the comparison of the two systems.

The main physics observable of interest in this analysis is the slope parameter (r^{norm}) extracted by fitting a linear function to the normalized v_n differences, $(v_n^- - v_n^+)/(v_n^- + v_n^+)$, as a function of the true event charge asymmetry value, $A_{\mathrm{ch}}^{\mathrm{true}}$, obtained by correcting $A_{\mathrm{ch}}^{\mathrm{obs}}$ for the detector acceptance and tracking efficiency. Based on Monte Carlo (MC) simulations, detector effects can be modeled as a Gaussian response of the $A_{\mathrm{ch}}^{\mathrm{true}}$ distribution within $|\eta| < 2.4$, with a width determined from the simulated $A_{\mathrm{ch}}^{\mathrm{obs}}$ distribution at a given $A_{\mathrm{ch}}^{\mathrm{true}}$ value. Combining the $A_{\mathrm{ch}}^{\mathrm{obs}}$ distribution in data with the response function from MC simulations, the predicted correlation between $A_{\mathrm{ch}}^{\mathrm{obs}}$ and $A_{\mathrm{ch}}^{\mathrm{true}}$ in data is calculated. The slope of a linear fit to this correlation is used to obtain the average $A_{\mathrm{ch}}^{\mathrm{true}}$

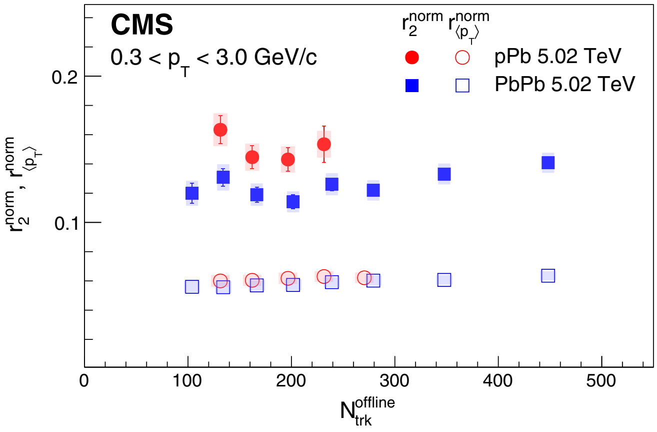

FIG. 4. The linear slope parameters r^{norm} for v_2 (filled symbols) and $\langle p_T \rangle$ (open symbols) as functions of event multiplicity in *p*Pb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

TABLE I. The table summarizes the absolute and normalized slope parameters (r) from v_2 and $\langle p_T\rangle$ in ranges of multiplicity class, $N_{\mathrm{trk}}^{\mathrm{offline}}$, in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The first uncertainty associated with the central values denotes statistical errors, while the second uncertainty represents the systematic uncertainty.

$N_{\mathrm{trk}}^{\mathrm{offline}}$	$r_{\langle v_2\rangle}$	$r_{\langle v_2\rangle}^{\mathrm{norm}}$	$r_{\langle p_T\rangle}$	$r_{\langle p_T\rangle}^{\mathrm{norm}}$
[120,150)	0.022 ± 0.001 ± 0.002	0.163 ± 0.01 ± 0.011	0.103 ± 0.001 ± 0.007	0.06 ± 0 ± 0.004
[150,185)	0.02 ± 0.001 ± 0.001	0.145 ± 0.008 ± 0.009	0.105 ± 0.001 ± 0.007	0.06 ± 0 ± 0.004
[185,220)	0.02 ± 0.001 ± 0.001	0.143 ± 0.008 ± 0.009	0.108 ± 0.001 ± 0.007	0.062 ± 0.001 ± 0.004
[220,260)	0.022 ± 0.002 ± 0.001	0.153 ± 0.012 ± 0.009	0.111 ± 0.002 ± 0.007	0.063 ± 0.001 ± 0.004

value in each selected $A_{\mathrm{ch}}^{\mathrm{obs}}$ range in data. The slope, which ranges from 0.6 to 0.8, is fit separately for each multiplicity or centrality selection. This procedure is validated using different MC generators, which give similar correction factors.

The systematic uncertainty related to the A_{ch} correction factors, based on the difference between EPOS LHC [42] and HYDJET++ [43] event generators, is estimated to be 1–7% ranging from high- to low-multiplicity events. To evaluate the systematic uncertainty related to the v_n measurement, the sensitivity of the results to different track selection criteria is studied. Varying the longitudinal and transverse track impact parameter selection criteria from the default three standard deviations to 2 or 5, and the relative p_T uncertainty selection criterion from the default 10% to 5%, yields a systematic uncertainty of less than 2%. The longitudinal primary vertex position (z_{vtx}) has been varied, using ranges $|z_{\mathrm{vtx}}| < 3$ cm and $3 < |z_{\mathrm{vtx}}| < 15$ cm, where the difference with respect to the default range $|z_{\mathrm{vtx}}| < 15$ cm is less than 2%. All of the systematic uncertainty sources are uncorrelated and were found to be similar for pPb and PbPb collisions. Therefore, the total systematic uncertainty is taken as the quadratic sum, and the same values are quoted for both pPb and PbPb systems.

V. RESULTS

Figure 2 (left column) shows the $A_{\mathrm{ch}}^{\mathrm{true}}$ dependence of v_2 coefficients, averaged over $0.3 < p_T < 3$ GeV/c, for positively and negatively charged particles in the multiplicity range $185 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 220$ of pPb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The normalized v_2 difference as a function of $A_{\mathrm{ch}}^{\mathrm{true}}$ is also shown. A trend of v_2^+ (v_2^-) decreasing (increasing) as $A_{\mathrm{ch}}^{\mathrm{true}}$ increases is observed for both pPb and PbPb collisions with an approximately linear dependence. A similar linear trend of elliptic anisotropy as a function of A_{ch} has been observed in AuAu [18] and PbPb [19] systems at lower collision energies, as shown in Fig. 3 for 30–40% centrality PbPb events. The linear slope parameter, r_2^{norm}, is extracted by a χ^2 fit to a linear function, which gives values of 0.149 ± 0.008 for pPb and 0.108 ± 0.005 for PbPb, in the multiplicity range $185 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 220$. A significant nonzero value of the linear slope parameter is observed in pPb collisions, even greater than that in PbPb collisions. Since the CMW effect is expected to be negligible in high-multiplicity pPb events, this observation might be caused, at LHC energies, by a mechanism unrelated to the CMW. The differences in the linear slope parameters observed in the pPb and PbPb systems remain to be understood.

The $\langle p_T\rangle$ for positively and negatively charged particles are also measured as functions of $A_{\mathrm{ch}}^{\mathrm{true}}$, in the multiplicity range $185 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 220$ of pPb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, and shown in Fig. 2 (right column). The normalized $\langle p_T\rangle$ difference as a function of $A_{\mathrm{ch}}^{\mathrm{true}}$ is obtained for the two systems with the slope parameters displayed in the figure. A similar linear $A_{\mathrm{ch}}^{\mathrm{true}}$ dependence of the $\langle p_T\rangle$ value to that of v_2 is observed. This behavior is qualitatively consistent with the expectation of the LCC effect from resonance decays. Since v_n has a strong dependence on particle p_T, a correlation between the p_T-averaged v_n and A_{ch}, as observed in Fig. 2 (left), can also be induced by the LCC mechanism.

The extracted normalized slope parameters for v_2 and $\langle p_T\rangle$ as functions of event multiplicity in pPb and PbPb collisions are shown in Fig. 4. The r^{norm} values for both v_2 and $\langle p_T\rangle$ are found to have a weak dependence on the event multiplicity for both pPb and PbPb collisions, with values for $\langle p_T\rangle$ approximately half of those for v_2. In the overlapping multiplicity range, normalized slope parameters are observed

TABLE II. The table summarizes the absolute and normalized slope parameters (r) from v_2 and $\langle p_T\rangle$ in ranges of multiplicity class, $N_{\mathrm{trk}}^{\mathrm{offline}}$, in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The first uncertainty associated with the central values denotes statistical errors, while the second uncertainty represents the systematic uncertainty.

$N_{\mathrm{trk}}^{\mathrm{offline}}$	$r_{\langle v_2\rangle}$	$r_{\langle v_2\rangle}^{\mathrm{norm}}$	$r_{\langle p_T\rangle}$	$r_{\langle p_T\rangle}^{\mathrm{norm}}$
[90,120)	0.02 ± 0.001 ± 0.001	0.12 ± 0.007 ± 0.009	0.084 ± 0.001 ± 0.006	0.056 ± 0 ± 0.004
[120,150)	0.023 ± 0.001 ± 0.002	0.131 ± 0.006 ± 0.009	0.084 ± 0.001 ± 0.006	0.056 ± 0.001 ± 0.004
[150,185)	0.022 ± 0.001 ± 0.001	0.119 ± 0.005 ± 0.008	0.087 ± 0.001 ± 0.006	0.057 ± 0.001 ± 0.004
[185,220)	0.022 ± 0.001 ± 0.001	0.108 ± 0.005 ± 0.007	0.087 ± 0.001 ± 0.006	0.058 ± 0.001 ± 0.004
[220,260)	0.025 ± 0.001 ± 0.001	0.126 ± 0.004 ± 0.008	0.091 ± 0.001 ± 0.005	0.059 ± 0.001 ± 0.004
[260,300)	0.025 ± 0.001 ± 0.001	0.122 ± 0.004 ± 0.007	0.093 ± 0.001 ± 0.005	0.06 ± 0.001 ± 0.003
[300,400)	0.028 ± 0 ± 0.001	0.133 ± 0.002 ± 0.007	0.094 ± 0.001 ± 0.005	0.061 ± 0 ± 0.003
[400,500)	0.03 ± 0 ± 0.001	0.141 ± 0.002 ± 0.007	0.099 ± 0.001 ± 0.005	0.064 ± 0.001 ± 0.003

TABLE III. The table summarizes the absolute and normalized slope parameters (r) from v_2 and v_3 in ranges of centrality class, in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The first uncertainty associated with the central values denotes statistical errors, while the second uncertainty represents the systematic uncertainty.

Centrality	$r_{\langle v_2 \rangle}$	$r^{\rm norm}_{\langle v_2 \rangle}$	$r_{\langle v_3 \rangle}$	$r^{\rm norm}_{\langle v_3 \rangle}$
30–40%	$0.032 \pm 0 \pm 0.001$	$0.162 \pm 0.001 \pm 0.006$	$0.01 \pm 0.0006 \pm 0.0004$	$0.149 \pm 0.008 \pm 0.006$
40–50%	$0.032 \pm 0 \pm 0.001$	$0.151 \pm 0.001 \pm 0.006$	$0.0102 \pm 0.0007 \pm 0.0004$	$0.15 \pm 0.01 \pm 0.006$
50–60%	$0.028 \pm 0 \pm 0.001$	$0.135 \pm 0.001 \pm 0.007$	$0.0083 \pm 0.001 \pm 0.0004$	$0.131 \pm 0.016 \pm 0.007$
60–70%	$0.024 \pm 0 \pm 0.002$	$0.126 \pm 0.002 \pm 0.008$	$0.0054 \pm 0.0016 \pm 0.0003$	$0.102 \pm 0.03 \pm 0.006$
70–80%	$0.022 \pm 0.001 \pm 0.002$	$0.136 \pm 0.004 \pm 0.011$	…	…
80–90%	$0.022 \pm 0.002 \pm 0.002$	$0.171 \pm 0.012 \pm 0.014$	…	…

to be larger in pPb than PbPb collisions, which is not expected in the CMW context and may indicate a collision system dependence of the LCC or other mechanisms. The measured normalized slope parameters, as well as the absolute slope parameters, for each multiplicity or centrality range of pPb and PbPb collisions, are reported in Tables I–III.

The charge asymmetry dependence of the v_3 coefficient for positively and negatively charged particles is also studied in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, as shown in Fig. 5 (top) for the 30–40% centrality class. As found for the v_2 values, the v_3^+ (v_3^-) values also decrease (increase) as $A_{\rm ch}^{\rm true}$ increases. No v_3 results for pPb collisions are reported because of limited statistical precision. The normalized v_3 difference, $(v_3^- - v_3^+)/(v_3^- + v_3^+)$, is derived as a function of $A_{\rm ch}^{\rm true}$ in PbPb collisions and compared with that for v_2 in Fig. 5 (bottom). The normalized slope parameter of v_3, $r_3^{\rm norm}$, agrees well with $r_2^{\rm norm}$ within statistical uncertainties. Charge-dependent higher harmonic v_n coefficients were measured in PbPb collisions at 2.76 TeV [5] and their magnitude was found to be smaller than that of the second order coefficient. We show in this paper that, once normalized, no difference is observed for the $A_{\rm ch}^{\rm true}$ dependence between the charge-dependent v_2 and v_3.

The $r_2^{\rm norm}$ and $r_3^{\rm norm}$ values of PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV are shown in Fig. 6, as functions of centrality in the range 30–90%. As found for $r_2^{\rm norm}$, a moderate centrality dependence of $r_3^{\rm norm}$ is observed. Over the centrality range studied in this analysis, the $r_2^{\rm norm}$ and $r_3^{\rm norm}$ slope parameters are consistent with each other within uncertainties. The CMW effect is expected with respect to the reaction plane, which is approximated by the second-order event plane in AA collisions, but highly suppressed with respect to the third-order event plane [13]. The observation of the harmonic order independence, reflected in the similar $r_2^{\rm norm}$ and $r_3^{\rm norm}$ values, indicates an underlying physics mechanism unrelated to the

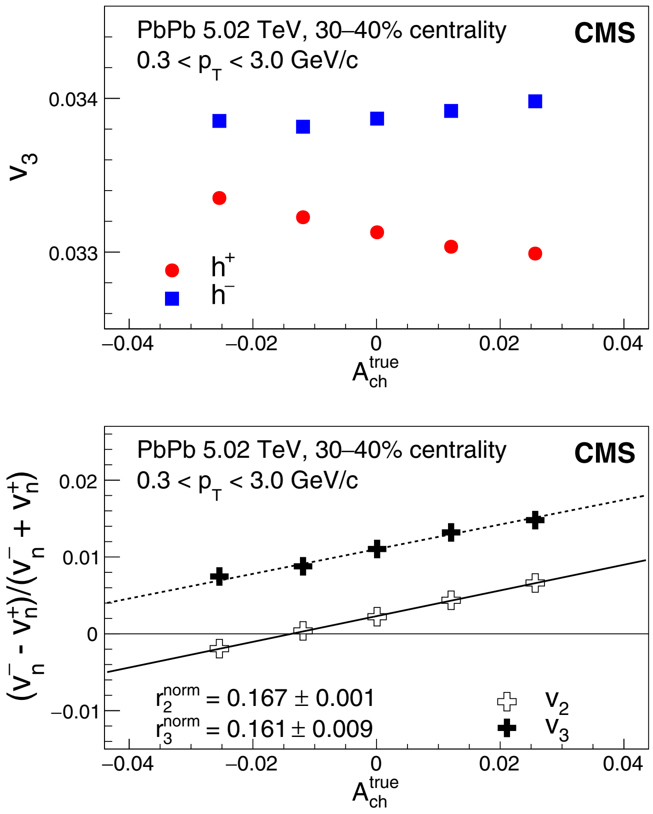

FIG. 5. The v_3 coefficient for positively and negatively charged particles (top) and the normalized difference in v_n, $(v_n^- - v_n^+)/(v_n^- + v_n^+)$ (bottom), for $n = 2$ and 3, as functions of true event charge asymmetry for the 30–40% centrality class in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV.

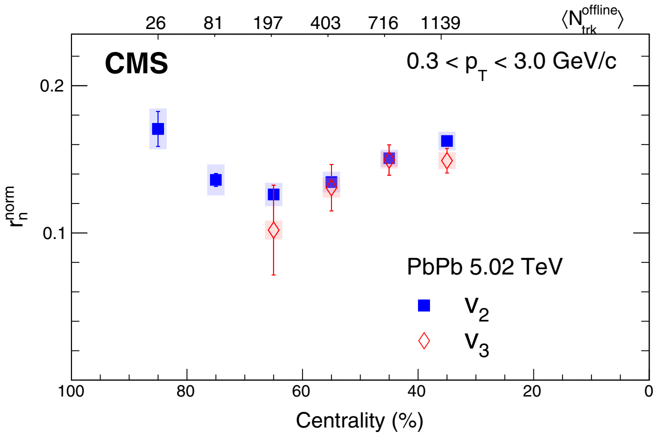

FIG. 6. The linear slope parameters, $r_2^{\rm norm}$ and $r_3^{\rm norm}$ as functions of the centrality class in PbPb collisions. Average $N_{\rm trk}^{\rm offline}$ values for each centrality class are indicated on the top axis. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

CMW effect and, instead, can be qualitatively explained by the LCC effect [20].

Note that the results reported here and elsewhere [18,19] used the same population of particles to measure both v_n and $A_{\rm ch}^{\rm true}$. However, the slope parameters are found to be reduced by about a factor of 3, if the $A_{\rm ch}^{\rm true}$ and v_n values are determined by two distinct groups of randomly selected particles. This suggests that the observed correlations are not of a collective nature.

VI. SUMMARY

In summary, the charge-dependent Fourier coefficients of the azimuthal anisotropy have been measured in *p*Pb and PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV as functions of the charge asymmetry of the produced hadrons. The normalized differences in the v_2 coefficient between positively and negatively charged particles in *p*Pb and PbPb, and that in the v_3 coefficient in PbPb collisions, are found to depend linearly on the charge asymmetry. The normalized slope parameters of the v_2 coefficient versus charge asymmetry in *p*Pb collisions are found to be significant and similar to those in PbPb collisions over a wide range of charged particle multiplicities. The normalized slope parameters of the v_2 and v_3 coefficients in PbPb collisions show similar magnitudes for various centrality classes. A significant charged asymmetry dependence is also observed for the event-averaged transverse momenta of positively and negatively charged particles in both *p*Pb and PbPb collisions. None of these observations, made at 5.02 TeV and within the CMS phase space window, are expected from the chiral magnetic wave as the dominant physics mechanism, while they are qualitatively consistent with predictions based on local charge conservation. The new measurements presented here indicate that, at LHC energies, the chiral magnetic wave is not the cause of the charge-dependent azimuthal anisotropies seen in *p*Pb and PbPb collisions.

ACKNOWLEDGMENTS

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie Curie program and the European Research Council and Horizon 2020 Grant, Contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), Contracts No. Harmonia 2014/14/M/ST2/00428, No. Opus 2014/13/B/ST2/02543, No. 2014/15/B/ST2/03998, and No. 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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