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

A. M. Sirunyan *et al.**
(CMS Collaboration)

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Charge-dependent anisotropy Fourier coefficients (v_n) of particle azimuthal distributions are measured in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ 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 pPb 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 pPb 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.

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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], $A_{\rm ch} \equiv (N_+ - N_-)/(N_+ + N_-)$, where N_+ and N_- denote the number of positively and negatively charged hadrons in each event,

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

Here $v_{2,\pm}^{\rm base}$ 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 $A_{\rm ch}$. Similar charge-dependent effects from the CMW are not expected for the third-order anisotropy coefficient (v_3) [13].

Recent observations of the $A_{\rm ch}$ 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 ($p_{\rm T}$) resonance tend to have a larger rapidity separation, resulting in

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*Full author list given at the end of the article.

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 $\langle p_{\text{T}}\rangle$ and of the p_{T}-averaged v_n coefficients in *p*Pb and PbPb collisions at $\sqrt{s_{_{\text{NN}}}} = 5.02$ 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 $\langle p_{\text{T}}\rangle$ 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 $1 < p_{\text{T}} < 10$ 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 $\sqrt{s_{_{\text{NN}}}} = 5.02$ TeV, collected in 2013 using the CMS detector, correspond to an integrated luminosity of 35 nb^{-1}. A subset of peripheral PbPb data at $\sqrt{s_{_{\text{NN}}}} = 5.02$ 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.

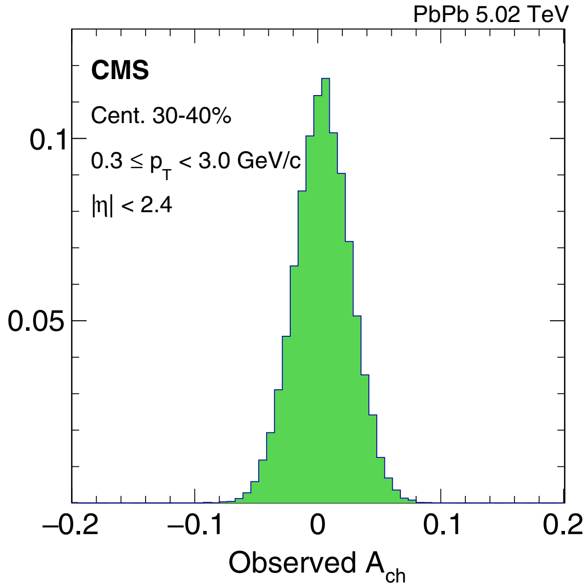

FIG. 1. The event-by-event probability distribution observed in the charge asymmetry, A_{ch}, for PbPb collisions at $\sqrt{s_{_{\text{NN}}}} = 5.02$ TeV within the 30–40% centrality range. The particles are selected between 0.3 and 3.0 GeV/*c* and having pseudorapidity $|\eta| < 2.4$.

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 ($N_{\text{trk}}^{\text{offline}}$) 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 $p_{\text{T}} > 0.3$ 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 $N_{\text{trk}}^{\text{offline}}$, where primary tracks with $|\eta| < 2.4$ and $p_{\text{T}} > 0.4$ GeV/*c* are counted, in order to match the trigger selection criterion implemented at the HLT in *p*Pb collisions.

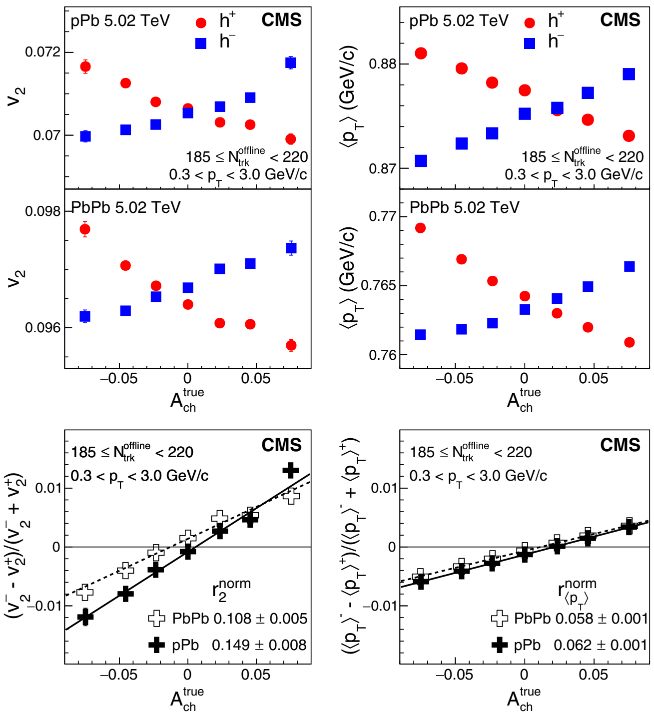

FIG. 2. The elliptic anisotropy v_2 (top left) and event-averaged $\langle p_T\rangle$ (top right) for positively (h^+) and negatively (h^-) charged particles, and their normalized differences (bottom row), as functions of $A_{\rm ch}^{\rm true}$ for the multiplicity range $185 \leqslant N_{\rm trk}^{\rm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

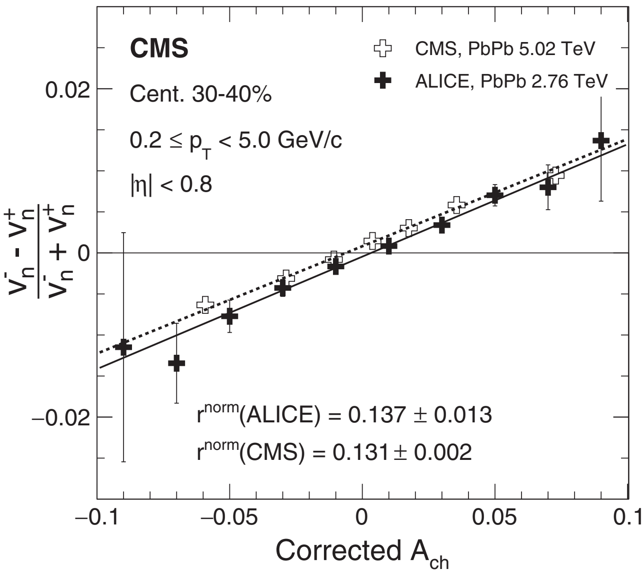

FIG. 3. The normalized difference in elliptic flow v_2 between positive- and negative-charged particles, $(v_2^- - v_2^+)/(v_2^- + v_2^+)$, as a function of charge asymmetry, is presented. The results are selected in centrality range 30–40% with particles within $|\eta| < 0.8$ and $0.2 \leqslant p_T < 5.0$ GeV, and are compared between the ALICE [19] and the CMS experiment in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ 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 $A_{\rm ch}^{\rm obs}$, calculated based on the number of positively and negatively charged particles from primary tracks. An example of the $A_{\rm ch}^{\rm obs}$ distribution for PbPb data in the 30–40% centrality range is shown in Fig. 1. Within each $A_{\rm ch}^{\rm obs}$ 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 $0.3 < p_T < 3\,{\rm GeV}/c$, 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 ($r^{\rm norm}$) 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, $A_{\rm ch}^{\rm true}$, obtained by correcting $A_{\rm ch}^{\rm obs}$ for the detector acceptance and tracking efficiency. Based on Monte Carlo (MC) simulations, detector effects can be modeled as a Gaussian response of the $A_{\rm ch}^{\rm true}$ distribution within $|\eta| < 2.4$, with a width determined from the simulated $A_{\rm ch}^{\rm obs}$ distribution at a given $A_{\rm ch}^{\rm true}$ value. Combining the $A_{\rm ch}^{\rm obs}$ distribution in data with the response function from MC simulations, the predicted correlation between $A_{\rm ch}^{\rm obs}$ and $A_{\rm ch}^{\rm true}$ in data is calculated. The slope of a linear fit to this correlation is used to obtain the average $A_{\rm ch}^{\rm true}$

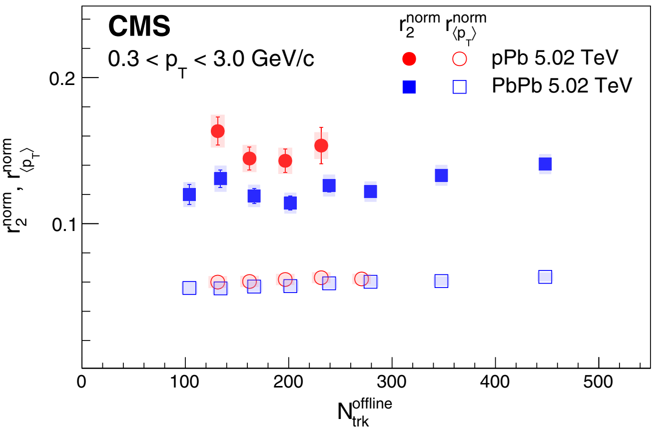

FIG. 4. The linear slope parameters $r^{\rm norm}$ for v_2 (filled symbols) and $\langle p_T\rangle$ (open symbols) as functions of event multiplicity in *p*Pb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, 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 *p*Pb 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)	$0.022 \pm 0.001 \pm 0.002$	$0.163 \pm 0.01 \pm 0.011$	$0.103 \pm 0.001 \pm 0.007$	$0.06 \pm 0 \pm 0.004$
[150,185)	$0.02 \pm 0.001 \pm 0.001$	$0.145 \pm 0.008 \pm 0.009$	$0.105 \pm 0.001 \pm 0.007$	$0.06 \pm 0 \pm 0.004$
[185,220)	$0.02 \pm 0.001 \pm 0.001$	$0.143 \pm 0.008 \pm 0.009$	$0.108 \pm 0.001 \pm 0.007$	$0.062 \pm 0.001 \pm 0.004$
[220,260)	$0.022 \pm 0.002 \pm 0.001$	$0.153 \pm 0.012 \pm 0.009$	$0.111 \pm 0.002 \pm 0.007$	$0.063 \pm 0.001 \pm 0.004$

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 *p*Pb and PbPb collisions. Therefore, the total systematic uncertainty is taken as the quadratic sum, and the same values are quoted for both *p*Pb 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 *p*Pb 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 *p*Pb 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 *p*Pb 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 *p*Pb collisions, even greater than that in PbPb collisions. Since the CMW effect is expected to be negligible in high-multiplicity *p*Pb 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 *p*Pb 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 *p*Pb 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 *p*Pb 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 *p*Pb 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)	$0.02 \pm 0.001 \pm 0.001$	$0.12 \pm 0.007 \pm 0.009$	$0.084 \pm 0.001 \pm 0.006$	$0.056 \pm 0 \pm 0.004$
[120,150)	$0.023 \pm 0.001 \pm 0.002$	$0.131 \pm 0.006 \pm 0.009$	$0.084 \pm 0.001 \pm 0.006$	$0.056 \pm 0.001 \pm 0.004$
[150,185)	$0.022 \pm 0.001 \pm 0.001$	$0.119 \pm 0.005 \pm 0.008$	$0.087 \pm 0.001 \pm 0.006$	$0.057 \pm 0.001 \pm 0.004$
[185,220)	$0.022 \pm 0.001 \pm 0.001$	$0.108 \pm 0.005 \pm 0.007$	$0.087 \pm 0.001 \pm 0.006$	$0.058 \pm 0.001 \pm 0.004$
[220,260)	$0.025 \pm 0.001 \pm 0.001$	$0.126 \pm 0.004 \pm 0.008$	$0.091 \pm 0.001 \pm 0.005$	$0.059 \pm 0.001 \pm 0.004$
[260,300)	$0.025 \pm 0.001 \pm 0.001$	$0.122 \pm 0.004 \pm 0.007$	$0.093 \pm 0.001 \pm 0.005$	$0.06 \pm 0.001 \pm 0.003$
[300,400)	$0.028 \pm 0 \pm 0.001$	$0.133 \pm 0.002 \pm 0.007$	$0.094 \pm 0.001 \pm 0.005$	$0.061 \pm 0 \pm 0.003$
[400,500)	$0.03 \pm 0 \pm 0.001$	$0.141 \pm 0.002 \pm 0.007$	$0.099 \pm 0.001 \pm 0.005$	$0.064 \pm 0.001 \pm 0.003$

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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The first uncertainty associated with the central values denotes statistical errors, while the second uncertainty represents the systematic uncertainty.

Centrality	$r_{\langle v_2\rangle}$	$r^{\mathrm{norm}}_{\langle v_2\rangle}$	$r_{\langle v_3\rangle}$	$r^{\mathrm{norm}}_{\langle v_3\rangle}$
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 *p*Pb 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 *p*Pb 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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 $A_{\mathrm{ch}}^{\mathrm{true}}$ increases. No v_3 results for *p*Pb 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 $A_{\mathrm{ch}}^{\mathrm{true}}$ in PbPb collisions and compared with that for v_2 in Fig. 5 (bottom). The normalized slope parameter of v_3, r_3^{norm}, agrees well with r_2^{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 $A_{\mathrm{ch}}^{\mathrm{true}}$ dependence between the charge-dependent v_2 and v_3.

The r_2^{norm} and r_3^{norm} values of PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are shown in Fig. 6, as functions of centrality in the range 30–90%. As found for r_2^{norm}, a moderate centrality dependence of r_3^{norm} is observed. Over the centrality range studied in this analysis, the r_2^{norm} and r_3^{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^{norm} and r_3^{norm} values, indicates an underlying physics mechanism unrelated to the

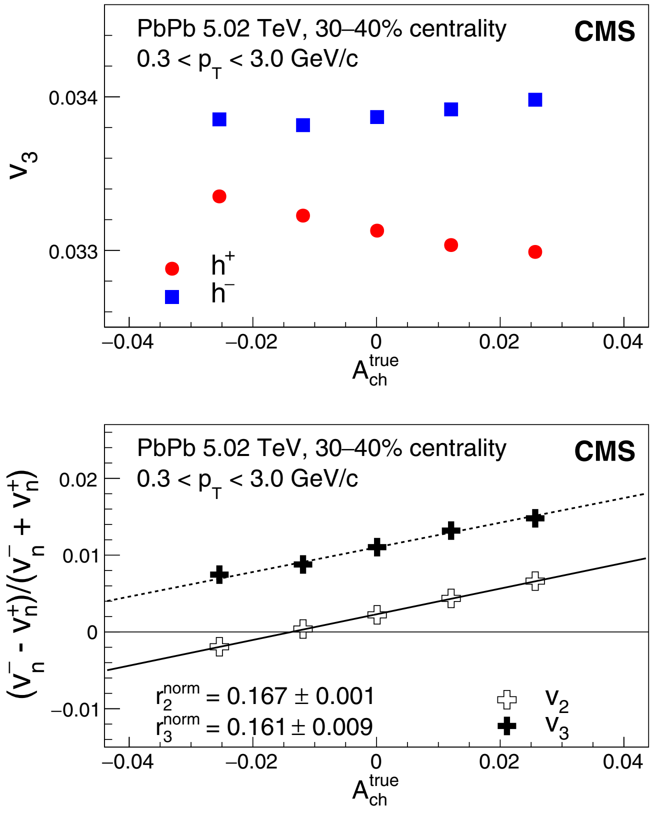

FIG. 5. The v_3 coefficient for positively and negatively charged particles (top) and the normalized difference in v_n, $(v_n^- - v_n^+)/(v_n^- + v_n^+)$ (bottom), for $n = 2$ and 3, as functions of true event charge asymmetry for the 30–40% centrality class in PbPb collisions at $\sqrt{s_{\mathrm{NN}}}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

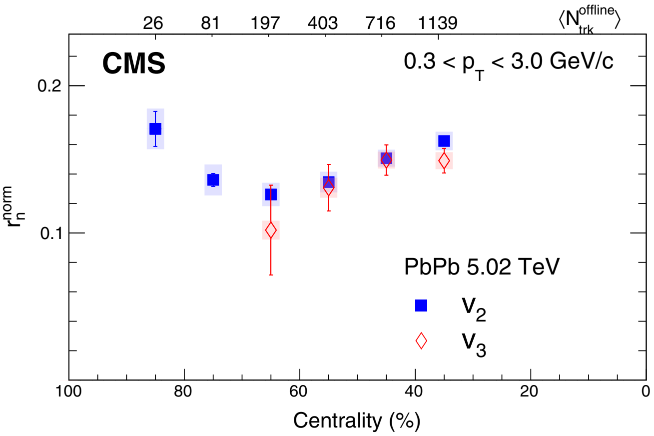

FIG. 6. The linear slope parameters, r_2^{norm} and r_3^{norm} as functions of the centrality class in PbPb collisions. Average $N_{\mathrm{trk}}^{\mathrm{offline}}$ values for each centrality class are indicated on the top axis. Statistical and systematic uncertainties are indicated by the error bars 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 $A_{\mathrm{ch}}^{\mathrm{true}}$. However, the slope parameters are found to be reduced by about a factor of 3, if the $A_{\mathrm{ch}}^{\mathrm{true}}$ 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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.

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Bodek,[170] P. de Barbaro,[170] R. Demina,[170] Y. t. Duh,[170] T. Ferbel,[170] M. Galanti,[170] A. Garcia-Bellido,[170] J. Han,[170] O. Hindrichs,[170] A. Khukhunaishvili,[170] K. H. Lo,[170] P. Tan,[170] M. Verzetti,[170] R. Ciesielski,[171] K. Goulianos,[171] C. Mesropian,[171] A. Agapitos,[172] J. P. Chou,[172] Y. Gershtein,[172] T. A. Gómez Espinosa,[172] E. Halkiadakis,[172] M. Heindl,[172] E. Hughes,[172] S. Kaplan,[172] R. Kunnawalkam Elayavalli,[172] S. Kyriacou,[172] A. Lath,[172] R. Montalvo,[172] K. Nash,[172] M. Osherson,[172] H. Saka,[172] S. Salur,[172] S. Schnetzer,[172] D. Sheffield,[172] S. Somalwar,[172] R. Stone,[172] S. Thomas,[172] P. Thomassen,[172] M. Walker,[172] A. G. Delannoy,[173] M. Foerster,[173] J. Heideman,[173] G. Riley,[173] K. Rose,[173] S. Spanier,[173] K. Thapa,[173] O. Bouhali,[174,bs] A. Castaneda Hernandez,[174,bs] A. Celik,[174] M. Dalchenko,[174] M. De Mattia,[174] A. Delgado,[174] S. Dildick,[174] R. Eusebi,[174] J. Gilmore,[174] T. Huang,[174] T. Kamon,[174,bt] R. Mueller,[174] Y. Pakhotin,[174] R. Patel,[174] A. Perloff,[174]

L. Perniè,[174] D. Rathjens,[174] A. Safonov,[174] A. Tatarinov,[174] K. A. Ulmer,[174] N. Akchurin,[175] J. Damgov,[175] F. De Guio,[175] P. R. Dudero,[175] J. Faulkner,[175] E. Gurpinar,[175] S. Kunori,[175] K. Lamichhane,[175] S. W. Lee,[175] T. Libeiro,[175] T. Peltola,[175] S. Undleeb,[175] I. Volobouev,[175] Z. Wang,[175] S. Greene,[176] A. Gurrola,[176] R. Janjam,[176] W. Johns,[176] C. Maguire,[176] A. Melo,[176] H. Ni,[176] P. Sheldon,[176] S. Tuo,[176] J. Velkovska,[176] Q. Xu,[176] M. W. Arenton,[177] P. Barria,[177] B. Cox,[177] R. Hirosky,[177] M. Joyce,[177] A. Ledovskoy,[177] H. Li,[177] C. Neu,[177] T. Sinthuprasith,[177] Y. Wang,[177] E. Wolfe,[177] F. Xia,[177] R. Harr,[178] P. E. Karchin,[178] J. Sturdy,[178] S. Zaleski,[178] M. Brodski,[179] J. Buchanan,[179] C. Caillol,[179] S. Dasu,[179] L. Dodd,[179] S. Duric,[179] B. Gomber,[179] M. Grothe,[179] M. Herndon,[179] A. Hervé,[179] U. Hussain,[179] P. Klabbers,[179] A. Lanaro,[179] A. Levine,[179] K. Long,[179] R. Loveless,[179] G. A. Pierro,[179] G. Polese,[179] T. Ruggles,[179] A. Savin,[179] N. Smith,[179] W. H. Smith,[179] D. Taylor,[179] and N. Woods[179]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Wien, Austria*
[3]*Institute for Nuclear Problems, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Université de Mons, Mons, Belgium*
[10]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[11]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[12a]*Universidade Estadual Paulista, São Paulo, Brazil*
[12b]*Universidade Federal do ABC, São Paulo, Brazil*
[13]*Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences*
[14]*University of Sofia, Sofia, Bulgaria*
[15]*Beihang University, Beijing, China*
[16]*Institute of High Energy Physics, Beijing, China*
[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[18]*Universidad de Los Andes, Bogota, Colombia*
[19]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[20]*University of Split, Faculty of Science, Split, Croatia*
[21]*Institute Rudjer Boskovic, Zagreb, Croatia*
[22]*University of Cyprus, Nicosia, Cyprus*
[23]*Charles University, Prague, Czech Republic*
[24]*Universidad San Francisco de Quito, Quito, Ecuador*
[25]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[26]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[27]*Department of Physics, University of Helsinki, Helsinki, Finland*
[28]*Helsinki Institute of Physics, Helsinki, Finland*
[29]*Lappeenranta University of Technology, Lappeenranta, Finland*
[30]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[31]*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*
[32]*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
[33]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
[34]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[35]*Georgian Technical University, Tbilisi, Georgia*
[36]*Tbilisi State University, Tbilisi, Georgia*
[37]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[38]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[39]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[40]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[41]*University of Hamburg, Hamburg, Germany*
[42]*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
[43]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
[44]*National and Kapodistrian University of Athens, Athens, Greece*
[45]*National Technical University of Athens, Athens, Greece*

[46]*University of Ioánnina, Ioánnina, Greece*
[47]*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[48]*Wigner Research Centre for Physics, Budapest, Hungary*
[49]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[50]*Institute of Physics, University of Debrecen, Debrecen, Hungary*
[51]*Indian Institute of Science (IISc), Bangalore, India*
[52]*National Institute of Science Education and Research, Bhubaneswar, India*
[53]*Panjab University, Chandigarh, India*
[54]*University of Delhi, Delhi, India*
[55]*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
[56]*Indian Institute of Technology Madras, Madras, India*
[57]*Bhabha Atomic Research Centre, Mumbai, India*
[58]*Tata Institute of Fundamental Research-A, Mumbai, India*
[59]*Tata Institute of Fundamental Research-B, Mumbai, India*
[60]*Indian Institute of Science Education and Research (IISER), Pune, India*
[61]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[62]*University College Dublin, Dublin, Ireland*
[63a]*INFN Sezione di Bari, Bari, Italy*
[63b]*Università di Bari, Bari, Italy*
[63c]*Politecnico di Bari, Bari, Italy*
[64a]*INFN Sezione di Bologna, Bologna, Italy*
[64b]*Università di Bologna, Bologna, Italy*
[65a]*INFN Sezione di Catania, Catania, Italy*
[65b]*Università di Catania, Catania, Italy*
[66a]*INFN Sezione di Firenze, Firenze, Italy*
[66b]*Università di Firenze, Firenze, Italy*
[67]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[68a]*INFN Sezione di Genova, Genova, Italy*
[68b]*Università di Genova, Genova, Italy*
[69a]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[69b]*Università di Milano-Bicocca, Milano, Italy*
[70a]*INFN Sezione di Napoli, Napoli, Italy*
[70b]*Università di Napoli 'Federico II', Napoli, Italy*
[70c]*Università della Basilicata, Potenza, Italy*
[70d]*Università G. Marconi, Roma, Italy*
[71a]*INFN Sezione di Padova, Padova, Italy*
[71b]*Università di Padova, Padova, Italy*
[71c]*Università di Trento, Trento, Italy*
[72a]*INFN Sezione di Pavia, Pavia, Italy*
[72b]*Università di Pavia, Pavia, Italy*
[73a]*INFN Sezione di Perugia, Perugia, Italy*
[73b]*Università di Perugia, Perugia, Italy*
[74a]*INFN Sezione di Pisa, Pisa, Italy*
[74b]*Università di Pisa, Pisa, Italy*
[74c]*Scuola Normale Superiore di Pisa, Pisa, Italy*
[75a]*INFN Sezione di Roma, Rome, Italy*
[75b]*Sapienza Università di Roma, Rome, Italy*
[76a]*INFN Sezione di Torino, Torino, Italy*
[76b]*Università di Torino, Torino, Italy*
[76c]*Università del Piemonte Orientale, Novara, Italy*
[77a]*INFN Sezione di Trieste, Trieste, Italy*
[77b]*Università di Trieste, Trieste, Italy*
[78]*Kyungpook National University, Daegu, Korea*
[79]*Chonbuk National University, Jeonju, Korea*
[80]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[81]*Hanyang University, Seoul, Korea*
[82]*Korea University, Seoul, Korea*
[83]*Seoul National University, Seoul, Korea*
[84]*University of Seoul, Seoul, Korea*

[85]*Sungkyunkwan University, Suwon, Korea*
[86]*Vilnius University, Vilnius, Lithuania*
[87]*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
[88]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[89]*Universidad Iberoamericana, Mexico City, Mexico*
[90]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[91]*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
[92]*University of Auckland, Auckland, New Zealand*
[93]*University of Canterbury, Christchurch, New Zealand*
[94]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[95]*National Centre for Nuclear Research, Swierk, Poland*
[96]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[97]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[98]*Joint Institute for Nuclear Research, Dubna, Russia*
[99]*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
[100]*Institute for Nuclear Research, Moscow, Russia*
[101]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[102]*Moscow Institute of Physics and Technology, Moscow, Russia*
[103]*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
[104]*P.N. Lebedev Physical Institute, Moscow, Russia*
[105]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[106]*Novosibirsk State University (NSU), Novosibirsk, Russia*
[107]*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
[108]*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
[109]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[110]*Universidad Autónoma de Madrid, Madrid, Spain*
[111]*Universidad de Oviedo, Oviedo, Spain*
[112]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[113]*CERN, European Union ropean Organization for Nuclear Research, Geneva, Switzerland*
[114]*Paul Scherrer Institut, Villigen, Switzerland*
[115]*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
[116]*Universität Zürich, Zurich, Switzerland*
[117]*National Central University, Chung-Li, Taiwan*
[118]*National Taiwan University (NTU), Taipei, Taiwan*
[119]*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
[120]*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
[121]*Middle East Technical University, Physics Department, Ankara, Turkey*
[122]*Bogazici University, Istanbul, Turkey*
[123]*Istanbul Technical University, Istanbul, Turkey*
[124]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
[125]*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[126]*University of Bristol, Bristol, United Kingdom*
[127]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[128]*Imperial College, London, United Kingdom*
[129]*Brunel University, Uxbridge, United Kingdom*
[130]*Baylor University, Waco, USA*
[131]*Catholic University of America, Washington DC, USA*
[132]*The University of Alabama, Tuscaloosa, USA*
[133]*Boston University, Boston, USA*
[134]*Brown University, Providence, USA*
[135]*University of California, Davis, Davis, USA*
[136]*University of California, Los Angeles, USA*
[137]*University of California, Riverside, Riverside, USA*
[138]*University of California, San Diego, La Jolla, USA*
[139]*University of California, Santa Barbara - Department of Physics, Santa Barbara, USA*
[140]*California Institute of Technology, Pasadena, USA*
[141]*Carnegie Mellon University, Pittsburgh, USA*
[142]*University of Colorado Boulder, Boulder, USA*
[143]*Cornell University, Ithaca, USA*

[144]*Fermi National Accelerator Laboratory, Batavia, USA*
[145]*University of Florida, Gainesville, USA*
[146]*Florida International University, Miami, USA*
[147]*Florida State University, Tallahassee, USA*
[148]*Florida Institute of Technology, Melbourne, USA*
[149]*University of Illinois at Chicago (UIC), Chicago, USA*
[150]*The University of Iowa, Iowa City, USA*
[151]*Johns Hopkins University, Baltimore, USA*
[152]*The University of Kansas, Lawrence, USA*
[153]*Kansas State University, Manhattan, USA*
[154]*Lawrence Livermore National Laboratory, Livermore, USA*
[155]*University of Maryland, College Park, USA*
[156]*Massachusetts Institute of Technology, Cambridge, USA*
[157]*University of Minnesota, Minneapolis, USA*
[158]*University of Mississippi, Oxford, USA*
[159]*University of Nebraska-Lincoln, Lincoln, USA*
[160]*State University of New York at Buffalo, Buffalo, USA*
[161]*Northeastern University, Boston, USA*
[162]*Northwestern University, Evanston, USA*
[163]*University of Notre Dame, Notre Dame, USA*
[164]*The Ohio State University, Columbus, USA*
[165]*Princeton University, Princeton, USA*
[166]*University of Puerto Rico, Mayaguez, USA*
[167]*Purdue University, West Lafayette, USA*
[168]*Purdue University Northwest, Hammond, USA*
[169]*Rice University, Houston, USA*
[170]*University of Rochester, Rochester, USA*
[171]*The Rockefeller University, New York, USA*
[172]*Rutgers, The State University of New Jersey, Piscataway, USA*
[173]*University of Tennessee, Knoxville, USA*
[174]*Texas A&M University, College Station, USA*
[175]*Texas Tech University, Lubbock, USA*
[176]*Vanderbilt University, Nashville, USA*
[177]*University of Virginia, Charlottesville, USA*
[178]*Wayne State University, Detroit, USA*
[179]*University of Wisconsin - Madison, Madison, WI, USA*

[a] Also at Vienna University of Technology, Vienna, Austria.

[b] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

[c] Also at Universidade Estadual de Campinas, Campinas, Brazil.

[d] Also at Universidade Federal de Pelotas, Pelotas, Brazil.

[e] Also at Université Libre de Bruxelles, Bruxelles, Belgium.

[f] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

[g] Also at Joint Institute for Nuclear Research, Dubna, Russia.

[h] Also at Suez University, Suez, Egypt; British University in Egypt, Cairo, Egypt.

[i] Also at Fayoum University, El-Fayoum, Egypt; British University in Egypt, Cairo, Egypt.

[j] Also at Helwan University, Cairo, Egypt.

[k] Also at Université de Haute Alsace, Mulhouse, France.

[l] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

[m] Also at Tbilisi State University, Tbilisi, Georgia.

[n] Also at Ilia State University, Tbilisi, Georgia.

[o] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

[p] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

[q] Also at University of Hamburg, Hamburg, Germany.

[r] Also at Brandenburg University of Technology, Cottbus, Germany.

[s] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

[t] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

[u] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

[v] Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

[w] Also at Institute of Physics, Bhubaneswar, India.

[x] Also at University of Visva-Bharati, Santiniketan, India.
[y] Also at University of Ruhuna, Matara, Sri Lanka.
[z] Also at Isfahan University of Technology, Isfahan, Iran.
[aa] Also at Yazd University, Yazd, Iran.
[ab] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[ac] Also at Università degli Studi di Siena, Siena, Italy.
[ad] Also at INFN Sezione di Milano-Bicocca, Milano, Italy; Università di Milano-Bicocca, Milano, Italy.
[ae] Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
[af] Also at Purdue University, West Lafayette, USA.
[ag] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[ah] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[ai] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[aj] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[ak] Also at Institute for Nuclear Research, Moscow, Russia; National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[al] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[am] Also at University of Florida, Gainesville, USA.
[an] Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[ao] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[ap] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[aq] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[ar] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[as] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[at] Also at National and Kapodistrian University of Athens, Athens, Greece.
[au] Also at Riga Technical University, Riga, Latvia.
[av] Also at Deceased.
[aw] Also at Universität Zürich, Zurich, Switzerland.
[ax] Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
[ay] Also at Adiyaman University, Adiyaman, Turkey.
[az] Also at Istanbul Aydin University, Istanbul, Turkey.
[ba] Also at Mersin University, Mersin, Turkey.
[bb] Also at Cag University, Mersin, Turkey.
[bc] Also at Piri Reis University, Istanbul, Turkey.
[bd] Also at Izmir Institute of Technology, Izmir, Turkey.
[be] Also at Necmettin Erbakan University, Konya, Turkey.
[bf] Also at Marmara University, Istanbul, Turkey.
[bg] Also at Kafkas University, Kars, Turkey.
[bh] Also at Istanbul Bilgi University, Istanbul, Turkey.
[bi] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[bj] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[bk] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[bl] Also at Utah Valley University, Orem, USA.
[bm] Also at Beykent University, Istanbul, Turkey.
[bn] Also at Bingol University, Bingol, Turkey.
[bo] Also at Erzincan University, Erzincan, Turkey.
[bp] Also at Sinop University, Sinop, Turkey.
[bq] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[br] Also at Institute for Nuclear Research, Moscow, Russia.
[bs] Also at Texas A&M University at Qatar, Doha, Qatar.
[bt] Also at Kyungpook National University, Daegu, Korea.