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Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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Measurements of charge-dependent azimuthal correlations with the ALICE detector at the LHC are reported for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Two- and three-particle charge-dependent azimuthal correlations in the pseudorapidity range $|\eta| < 0.8$ are presented as a function of the collision centrality, particle separation in pseudorapidity, and transverse momentum. A clear signal compatible with a charge-dependent separation relative to the reaction plane is observed, which shows little or no collision energy dependence when compared to measurements at RHIC energies. This provides a new insight for understanding the nature of the charge-dependent azimuthal correlations observed at RHIC and LHC energies.

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The possibility to observe parity violation in the strong interaction using relativistic heavy-ion collisions has been discussed for many years [1–3]. In quantum chromodynamics (QCD), this symmetry violation originates in the interaction between quarks and topologically nontrivial gluonic fields, instantons, and sphalerons [4]. This interaction, which is characterized by the topological charge [5], breaks the balance between the number of quarks with different chirality, resulting in a violation of the P and CP symmetry. In [6,7], it was suggested that in the vicinity of the deconfinement phase transition, and under the influence of the strong magnetic field generated by the colliding nuclei, the quark spin alignment along the direction of the angular momentum (i.e. the direction of the magnetic field) and the imbalance of the left- and right-handed quarks, generates an electromagnetic current. The experimental search of these effects has intensified recently, following the realization that the consequent quark fragmentation into charged hadrons results in a charge separation along the direction of the magnetic field, and perpendicular to the reaction plane (the plane of symmetry of a collision defined by the impact parameter vector and the beam direction). This phenomenon is called the chiral magnetic effect (CME). Because of fluctuations in the sign of the topological charge, the resulting charge separation averaged over many collisions is zero. This makes the observation of the CME possible only via P-even observables, expressed in terms of two-particle and multiparticle correlations. The previous measurement of charge separation by the STAR Collaboration [8] is consistent with the qualitative expectations for the CME and has triggered an intense discussion [9–13].

A significant source of uncertainty in the theoretical consideration of the CME is related to the expected center-of-mass energy dependence. In [7], the authors argued that the uncertainty in making any quantitative prediction relies on the time integration over which the magnetic field develops and decays. As long as a deconfined state of matter is formed in a heavy-ion collision, the magnitude of the effect should either not change or should decrease with increasing energy [7]. In addition, in [12] it is also suggested that there should be no energy dependence between the top RHIC and the LHC energies, based on arguments related to the universality of the underlying physical process, without however explicitly quantifying what the contribution of the different values and time evolution of the magnetic field for different energies will be. On the other hand, in [13] it is argued that the CME should strongly decrease at higher energies, because the magnetic field decays more rapidly. Such spread in the theoretical expectations makes it important to measure the charge-dependent azimuthal correlations at the LHC, where the collision energy is an order of magnitude higher compared to the RHIC.

In this Letter we report the measurement of charge-dependent azimuthal correlations at midrapidity in Pb-Pb collisions at the center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV by the ALICE Collaboration at the LHC.

Azimuthal correlations among particles produced in a heavy-ion collision provide a powerful tool for the experimental study of particle production with respect to the reaction plane. They are usually quantified by the anisotropic flow coefficients, v_n, in a Fourier decomposition [14]. Local violation of parity symmetry may result in the additional P-odd sinus terms [3,8,15]:

$$\frac{dN}{d\varphi_\alpha} \sim 1 + 2\sum_n [v_{n,\alpha}\cos(n\Delta\varphi_\alpha) + a_{n,\alpha}\sin(n\Delta\varphi_\alpha)], \quad (1)$$

where $\Delta\varphi_\alpha = \varphi_\alpha - \Psi_{\mathrm{RP}}$ is the azimuthal angle φ_α of the charged particle of type α relative to the reaction plane

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angle, $\Psi_{\rm RP}$. The leading order coefficient $a_{1,\alpha}$ reflects the magnitude while the higher orders ($a_{n,\alpha}$ for $n > 1$) describe the specific shape in azimuth of the effects from local parity violation. We thus employ a multiparticle correlator [15] that probes the magnitude of the a_1 coefficient, and at the same time suppresses the background correlations unrelated to the reaction plane:

$$\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP})\rangle = \langle\cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle - \langle\sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta\rangle. \quad (2)$$

The indices α and β refer to the charge of the particles. The brackets denote an average over the particle pairs within the event as well as an average over the analyzed events. In practice, the reaction plane angle is not known and is estimated by constructing the event plane using azimuthal particle distributions. In Eq. (2), the terms $\langle\cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle$ and $\langle\sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta\rangle$ quantify the correlations in- and out-of plane, respectively. The latter is sensitive to the charge correlations resulting from the CME: $\langle\sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta\rangle \sim \langle a_{1,\alpha} a_{1,\beta}\rangle$. The construction of the correlator in Eq. (2) as the difference between these two contributions suppresses correlations not related to the reaction plane orientation (nonflow). The contribution from the CME to the correlations of pairs of particles with same and opposite charge is expected to be similar in magnitude and opposite in sign. This expectation could be further modified by the medium created in a heavy-ion collision, that may result in the dilution of the correlations between particles with opposite sign [6,7]. In order to evaluate each of the two terms in Eq. (2), we also measure the two-particle correlator:

$$\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle = \langle\cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle + \langle\sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta\rangle, \quad (3)$$

which in contrast to the correlator in Eq. (2) is independent of the reaction plane angle and susceptible to the large P-even background contributions. The combination of these correlators provides access to both components, $\langle\cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle$ and $\langle\sin\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle$, which is important for detailed comparisons with model calculations.

It should be pointed out that both correlators of Eq. (2) and Eq. (3) could be affected by background sources. In [10], it is argued that the effect of momentum conservation influences in a similar way the pairs of particles with opposite and same charge, and could result in a potentially significant correction to both $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP})\rangle$ and $\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$. Also in [10], it was suggested that local charge conservation effects may be responsible for a significant part of the observed charge dependence of the correlator $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP})\rangle$. Recent calculations [16] suggest that the correlator in Eq. (2) may have a negative (i.e. out-of-plane), charge-independent, dipole flow contribution originating from fluctuations in the initial energy density of a heavy-ion collision.

A description of the ALICE detector and its performance can be found in [17,18]. For this analysis, the following detector subsystems were used: the time projection chamber (TPC) [19], the silicon pixel detector (SPD), two forward scintillator arrays (VZERO), and two zero degree calorimeters (ZDC) [17].

We analyzed a sample of about 13×10^6 minimum-bias trigger events of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV collected with the ALICE detector. The standard ALICE offline event selection criteria [20] were applied, including a collision vertex cut of ± 7 cm along the beam axis. The collision centrality is estimated from the amplitude measured by the VZERO detectors [17]. The data sample is divided into centrality classes which span 0%-70% of the hadronic interaction cross section, with the 0%-5% class corresponding to the most central (i.e. smaller impact parameter) collisions. Charged particles reconstructed by the TPC are accepted for analysis within $|\eta| < 0.8$ and $0.2 < p_{\rm T} < 5.0$ GeV/c. A set of requirements described in [20] were applied in order to ensure the quality of the tracks but also to reduce the contamination from secondary particles.

To evaluate the systematic uncertainties in the analysis, events recorded with two different magnetic field polarities were analyzed leading to an uncertainty that is less than 7% for all centrality classes. The cut on the collision vertex was varied from ± 7 cm to ± 10 cm from the nominal collision point, with steps of 1 cm, contributing a maximum of 5% to the total uncertainty. A bias due to the centrality determination was studied by using multiplicities measured by the TPC or the SPD, rather than the VZERO, and was found to be less than 10%. Contamination due to secondary tracks that do not originate from the collision vertex was reduced by requiring that the distance of closest approach between tracks and the primary vertex is less than 2 cm. The effect of secondary tracks on the measurement was estimated by varying the cut from 2 to 4 cm in steps of 0.5 cm and was calculated to be below 15%. Effects due to nonuniform acceptance of the TPC were estimated to be below 2% and are corrected for in the analysis. A significant contribution to the systematic error is coming from the uncertainty in the v_2 measurement, which is used as an estimate of the reaction plane resolution. The v_2 estimate is obtained from the 2- and 4-particle cumulant analyses [20], which are affected in different ways by nonflow effects and flow fluctuations. For this analysis, v_2 was taken as the average of the two values, with half of the difference between $v_2\{2\}$ and $v_2\{4\}$ being attributed as the systematic uncertainty. The values of this uncertainty range from 9% for the 20%–30% centrality to 18% (24%) for the 50%–60% (60%–70%) centrality class. The differences in the results from the four independent analysis methods (described below) were also considered as part of the systematic uncertainty and were estimated to be 3% for the 20%–30% and the 50%–60% centrality bins and 47% for the most peripheral centrality class. The contributions from all effects were added in quadrature to calculate the total

systematic uncertainty. For the correlation between pairs of particles with the same charge it varies from 19% (28%) for the 20%–30% (50%–60%) centrality up to 55% for the 60%–70% centrality class. The correlations between opposite charged particles for 0%–60% centrality and for the same charge pairs for 0%–20% centrality are compatible with zero with a systematic error below 5.5×10^{-5}.

Figure 1(a) presents the centrality dependence of the three-particle correlator, defined in Eq. (2). The correlations of the same charge pairs for the positive-positive and negative-negative combinations are found to be consistent within statistical uncertainties and are combined into one set of points, labeled *same*. The difference between the correlations of pairs with same and opposite charge indicates a charge dependence with respect to the reaction plane, as may be expected for the CME. To test the bias from the reaction plane reconstruction, four independent analyses were performed. The first analysis uses a cumulant technique [21], whereas for the three other analyses the orientation of the collision symmetry plane is estimated from the azimuthal distribution of charged particles in the TPC, and hits in the forward VZERO and ZDC detectors [22]. There is a very good agreement between the results obtained with the event plane estimated from different detectors covering a wide range in pseudorapidity. This allows us to conclude that background sources due to correlations not related to the orientation of the reaction plane are negligible, with perhaps the exception of the peripheral collisions for the pairs of particles with opposite charge.

Figure 1(b) shows the centrality dependence of the two-particle correlator $\langle \cos(\varphi_\alpha - \varphi_\beta) \rangle$, as defined in Eq. (3), which helps to constrain experimentally the P-even background correlations. The statistical uncertainty is smaller than the symbol size. The two-particle correlations for the same and opposite charge combinations are always positive and exhibit qualitatively similar centrality dependence, while the magnitude of the correlation is smaller for the same charged pairs. Our two-particle correlation results differ from those reported by the STAR Collaboration for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [8] for which negative correlations are observed for the same charged pairs.

Figure 1(c) shows the $\langle \cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta \rangle$ and $\langle \sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta \rangle$ terms separately. For pairs of particles of the same charge, we observe that the $\langle \sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta \rangle$ correlations are larger than the $\langle \cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta \rangle$ ones. On the other hand, for pairs of opposite charge, the two terms are very close except for the most peripheral collisions. Further interpretation of the results presented in Fig. 1(c) in terms of in- and out-of-plane correlations is complicated due to the significant nonflow contribution in $\langle \cos(\varphi_\alpha - \varphi_\beta) \rangle$.

Figure 2 presents the three-particle correlator $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\mathrm{RP}}) \rangle$ as a function of the collision centrality compared to model calculations and results for RHIC energies. The statistical uncertainties are represented by the error

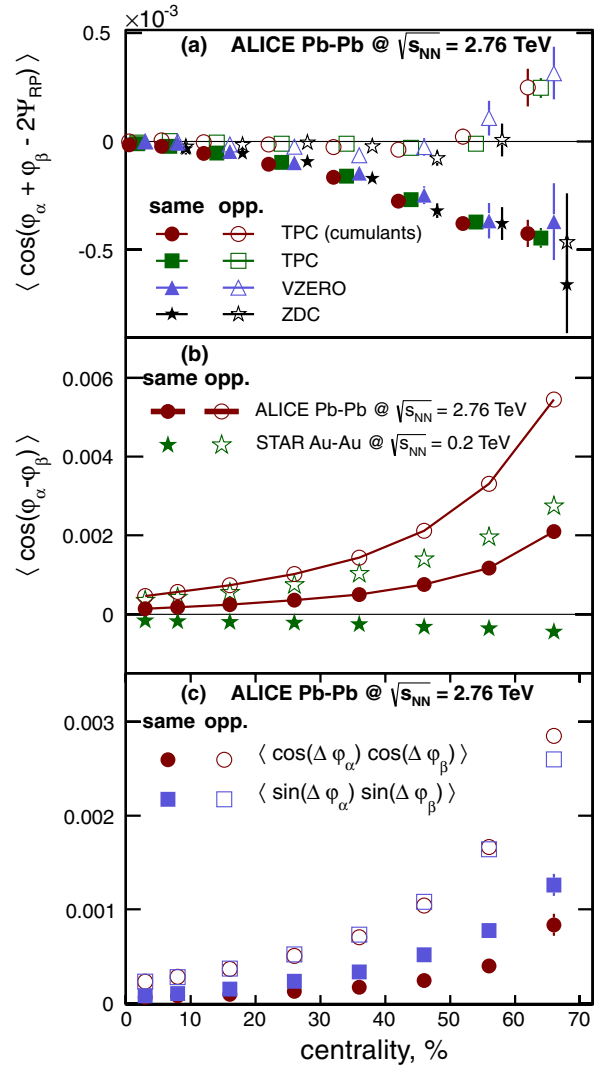

FIG. 1 (color online). (a) Centrality dependence of the correlator defined in Eq. (2) measured with the cumulant method and from correlations with the reaction plane estimated using the TPC, the ZDC, and the VZERO detectors. Only statistical errors are shown. The points are displaced slightly in the horizontal direction for visibility. (b) Centrality dependence of the two-particle correlator defined in Eq. (3) compared to the STAR data [8]. The width of the solid red lines indicates the systematic uncertainty of the ALICE measurement. (c) Decomposition of the correlators into $\langle \cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta \rangle$ and $\langle \sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta \rangle$ terms. The ALICE results in (b) and (c) are obtained with the cumulant method.

bars. The shaded area around the points indicates the systematic uncertainty based on the different sources described above. Also shown in Fig. 2 are STAR results [8]. The small difference between the LHC and the RHIC data indicates little or no energy dependence for the three-particle correlator when changing from the collision energy of $\sqrt{s_{NN}} = 0.2$ TeV to 2.76 TeV.

In Fig. 2, the ALICE data are compared to the expectations from the HIJING model [23]. The HIJING results for the three-particle correlations are divided by the experimentally

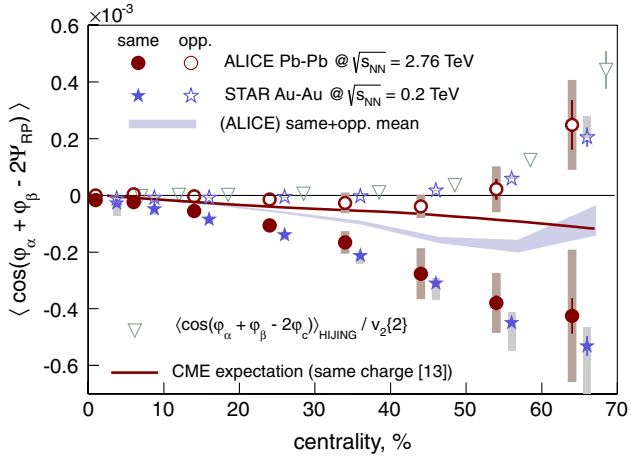

FIG. 2 (color online). The centrality dependence of the three-particle correlator defined in Eq. (2). The circles indicate the ALICE results obtained from the cumulant analysis. The stars show the STAR data from [8]. The triangles represent the three-particle correlations [$\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_c)\rangle$] from HIJING [23] corrected for the experimentally measured $v_2\{2\}$ [20]. Points are displaced horizontally for visibility. A model prediction for the same sign correlations incorporating the chiral magnetic effect for LHC energies [13] is shown by the solid line. The shaded band represents the centrality dependence of the charge-independent correlations.

measured value of v_2 (i.e. $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_c)\rangle/v_2\{2\}$) as reported in [20] due to the absence of collective azimuthal anisotropy in this model. Since the points do not exhibit any significant difference between the correlations of pairs with same and opposite charge, they were averaged in the figure. The correlations from HIJING show a significant increase in the magnitude for very peripheral collisions. This can be attributed to correlations not related to the reaction plane orientation, in particular, from jets [8].

The results from ALICE in Fig. 2 show a strong correlation for pairs with the same charge and simultaneously a very weak correlation for the pairs of opposite charge. This difference in the correlation magnitude depending on the charge combination could be interpreted as "quenching" of the charge correlations for the case when one of the particles is emitted toward the center of the dense medium created in a heavy-ion collision [6,7]. An alternative explanation can be provided by a recent suggestion [16] that the value of the charge-independent version of the correlator defined in Eq. (2) is dominated by directed flow fluctuations. The sign and the magnitude of these fluctuations based on a hydrodynamical model calculation for RHIC energies [16] appear to be very close to the measurement. Our results for charge-independent correlations are given by the shaded band in Fig. 2.

The thick solid line in Fig. 2 shows a prediction [13] for the same sign correlations due to the CME at LHC energies. The model makes no prediction for the absolute magnitude of the effect and can only describe the energy dependence by taking into account the duration and time evolution of the magnetic field. It predicts a decrease of correlations by about a factor of 5 from RHIC to LHC, which would significantly underestimate the observed magnitude of the same sign correlations seen at the LHC. At the same time in [7,12], it was suggested that the CME might have the same magnitude at the LHC and at RHIC energies.

Figure 3 shows the dependence of the three-particle correlator on the transverse momentum difference, $|p_{T,\alpha} - p_{T,\beta}|$, the average transverse momentum, $(p_{T,\alpha} + p_{T,\beta})/2$, and the pseudorapidity separation, $|\eta_\alpha - \eta_\beta|$, of the pair for the 30%-40% centrality range. The pairs of opposite charge do not show any significant dependence on the pseudorapidity difference, while there is a dependence

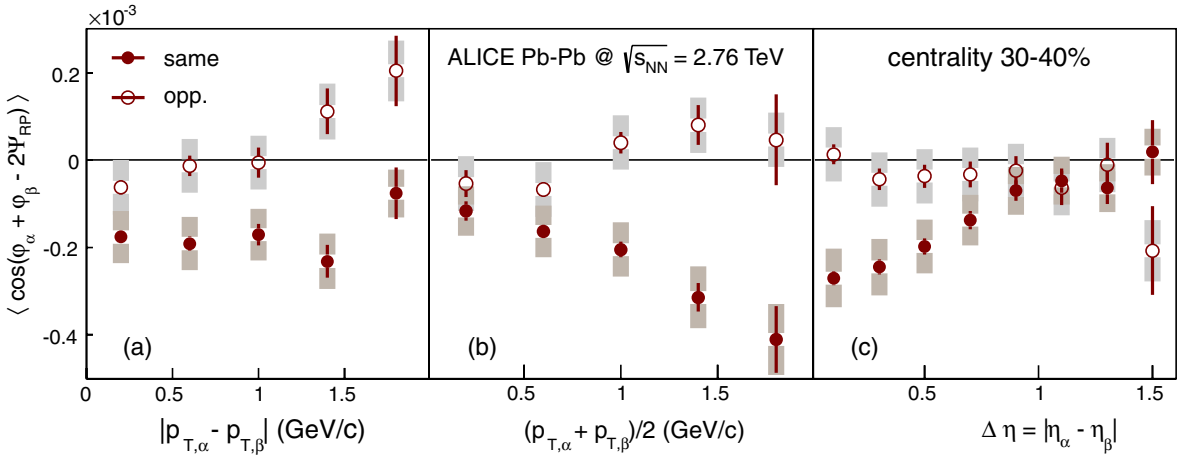

FIG. 3 (color online). The three-particle correlator defined in Eq. (2) as a function of (a) the transverse momentum difference, $|p_{T,\alpha} - p_{T,\beta}|$, (b) the average transverse momentum, $(p_{T,\alpha} + p_{T,\beta})/2$, and (c) the rapidity separation, $|\eta_\alpha - \eta_\beta|$, of the charged particle pair of same (closed symbols) and opposite (open symbols) sign.

on $|p_{T,\alpha} - p_{T,\beta}|$ (stronger) and $(p_{T,\alpha} + p_{T,\beta})/2$ (weaker). The correlations for pairs of particles of the same charge show no strong dependence on the p_T difference, allowing one to exclude any type of short range correlations (e.g. quantum statistics correlations) as the main source of the effect. In addition, it is seen that the magnitude of the same charge correlations increases with increasing average p_T of the pair. This observation is in contradiction to the initial expectations from theory [7] that the effect should originate from low p_T particles. The dependence of the correlations on the $|\eta_\alpha - \eta_\beta|$ indicates a width of one unit in pseudorapidity, beyond which the value of $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle$ is close to zero up to $\Delta\eta \approx 1.5$. Similar results were reported also at RHIC energies [8]. At the moment there are no quantitative model calculations of the charge-dependent differential correlations.

In summary, we have measured the charge-dependent azimuthal correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC using the ALICE detector. Both two- and three-particle correlations are reported. A clear signal compatible with a charge-dependent separation relative to the reaction plane is observed. However, our results are not described by the only available quantitative model prediction of the CME for the LHC energy. The lack of realistic model calculations for the centrality and pair differential dependencies based on models incorporating CME and possible background contributions does not allow us to make a firm conclusion regarding the nature of the charge-dependent correlations originally observed at RHIC and now established at the LHC. The observation of a small collision energy dependence of the three-particle correlation and the simultaneous significant change in the two-particle correlations between top RHIC and LHC energies put stringent constraints on models built to interpret such correlations. Analyses of higher harmonic correlations are planned and may yield a better understanding of the complex charge-dependent correlations seen at LHC energies.

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