MIXED HARMONIC CHARGE DEPENDENT AZIMUTHAL CORRELATIONS IN Pb–Pb COLLISIONS AT $\sqrt{s_{NN}} = 2.76$ TeV MEASURED WITH THE ALICE EXPERIMENT AT THE LHC*

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Mixed harmonic charge dependent azimuthal correlations at mid-rapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV were measured with the ALICE detector at the LHC. A clear charge dependence for a series of correlations is observed both via the multi-particle cumulant and the event plane methods. Implications from these measurements for the possible effects of local parity violation in QCD and for models which incorporate azimuthal anisotropic flow and "effective" local charge conservation on the kinetic freeze-out surface are discussed.

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1. Introduction

The charge dependence of azimuthal correlations between produced hadrons is an important probe of QGP matter created in relativistic heavy-ion collisions. It is, in particular, sensitive to the interplay between the local charge conservation (LCC) induced correlations and azimuthally asymmetric radial expansion of the collision system [1].

Recently, it was argued that the charge dependent azimuthal correlations can be also sensitive to the possible effect of local parity violation in QCD [2]. Parity violation in QCD may happen as a result of the interaction between produced quarks and topologically non-trivial gluonic field configurations. In the presence of the strong magnetic field generated in a heavy-ion collision, local parity violation may result in a separation of charges along the magnetic field which points perpendicular to the reaction plane. This phenomenon is called the Chiral Magnetic Effect (CME).

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An important observable, which was proposed as a sensitive probe of the CME, is the two particle correlation with respect to the reaction plane $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP})\rangle$ [3], where the bracket denotes the average over all particles in all events and the indices α and β refer to the charge of the particles. $\varphi_{\alpha,\beta}$ is the azimuthal angle of the charged particles and $\Psi_{\rm RP}$ is the reaction plane angle. In the presence of the CME, this correlation can be decomposed as

$$\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP})\rangle \;\sim\; -\langle a_\alpha a_\beta\rangle + B_{\rm in} - B_{\rm out}\,,$$

where $a_{\alpha,\beta}$ indicates the charge asymmetry due to the CME. The average $\langle a_\alpha a_\beta\rangle$ is expected to be positive for the same charge combination and negative for the opposite charge combination. $B_{\rm in/out}$ denotes the backgrounds when both two particles are in the in-plane/out-of-plane region. Measurements by the STAR Collaboration revealed non-zero charge dependent and independent parts of the correlation $\langle\cos(\varphi_\alpha+\varphi_\beta-2\Psi_{\rm RP})\rangle$, which are consistent with qualitative expectations from the CME [4]. However, a study [1] showed that a significant part of the observed charge dependent part can be described by the Blast Wave model incorporating effects of LCC on the kinetic freeze-out surface. Furthermore, the charge independent part may have non-zero contributions from directed flow fluctuations and effects of momentum conservation [5, 6].

Recently, the ALICE Collaboration released a paper [7], where the correlation $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP})\rangle$ were measured at the LHC energy. In these proceedings, we extend the ALICE measurement with additional mixed harmonic charge dependent correlations, which may help to disentangle the CME and LCC induced correlations [9]. We present the correlations $\Delta\langle\cos[n(\varphi_\alpha - \varphi_\beta)]\rangle$ and $\Delta\langle\cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_2]\rangle$, where n, m are integers and Ψ_2 is an azimuthal angle of the 2nd order collision symmetry plane. Here, Δ denotes the difference between the same and opposite charge correlations. In terms of the LCC, the charge dependent part of the correlation $\Delta\langle\cos[n(\varphi_\alpha - \varphi_\beta)]\rangle$ measures moments of the azimuthal distribution between balancing charges. The first moment ($n = 1$) is connected to the inverse width of the distribution of the balancing charges, which is sensitive to the radial expansion of the system. Similarly, the charge dependent part of the correlation $\Delta\langle\cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_2]\rangle$ measures a modulation of charge balancing width due to the m-harmonic anisotropic flow relative to the 2nd collision order symmetry plane.

2. Analysis details

A sample of about 13 M minimum bias Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV collected by the ALICE detector during the 2010 LHC run was analyzed. A description of the ALICE detector and details about collision

triggers and centrality determination can be found in [7, 8]. A Time Projection Chamber (TPC) is used to reconstruct charged particles in the kinematic range $|\eta| < 0.8$ and $p_{\mathrm{T}} > 0.2$ GeV/c. Correlations with respect to the symmetry plane were measured using the event plane and multi-particle cumulant methods. In the event plane method, the symmetry planes were estimated from azimuthal distributions of hits in two forward scintillator counters (VZERO) which cover the pseudo-rapidity range $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$, and two Forward Multiplicity Detectors (FMD) located at $1.7 < \eta < 5.1$ and $-3.4 < \eta < -1.7$. In the multi-particle cumulant method, the correlations with respect to the symmetry plane are evaluated from the azimuthal angle correlations of charged particles reconstructed by the TPC. Although the dominant systematic errors come from the event plane determinations, we observed good agreement between results from the different methods.

3. Results

The centrality dependence of the correlations $\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$ and $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\mathrm{RP}})\rangle$ for the same and opposite charge combinations measured for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was reported by ALICE in [7]. For the correlation $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\mathrm{RP}})\rangle$, ALICE observed that the same charge correlation is non-zero and negative, while the opposite charge correlation has a significantly smaller magnitude and is positive for peripheral collisions. ALICE also showed that there is little collision energy dependence when comparing results to that at the top RHIC energy. Even though some of the features of the observed correlations are in qualitative agreement with the expectation from the CME, origins of both charge dependent and independent parts are still not clear since they are also sensitive to many other parity-conserving physics mechanisms. To study the physics backgrounds for the CME search, ALICE has measured the two particle correlation $\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$, which also shows strong charge dependence but its correlation strength is significantly different from what was measured by the STAR Collaboration at lower collision energy. This correlation may have a contribution of the CME,

$$\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle \;\sim\; \langle a_\alpha a_\beta\rangle + B_{\mathrm{in}} + B_{\mathrm{out}}\,,$$

but its measurement is expected to be dominated by the large background correlations $B_{\mathrm{in}} + B_{\mathrm{out}}$, and, in particular, by those unrelated to the reaction plane orientation (non-flow).

As shown in Fig. 1, measurements were extended to a set of charge dependent correlations, which help to better constrain the possible physical contributions to the previously measured correlation $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\mathrm{RP}})\rangle$.

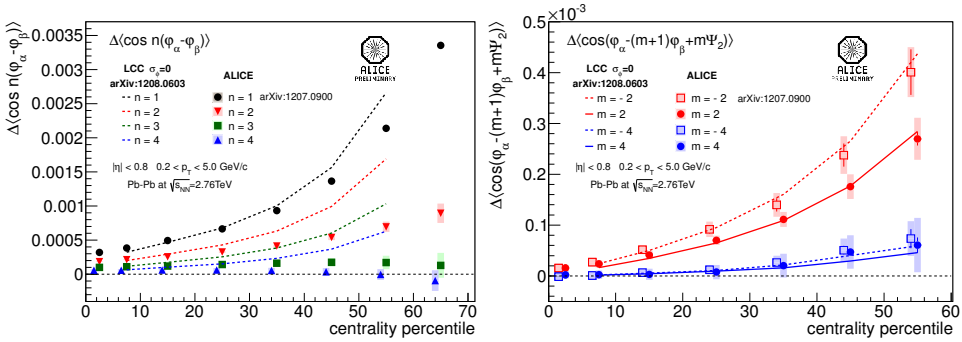

Fig. 1. Centrality dependence of the charge dependent part of the correlation (left) $\Delta\langle\cos[n(\varphi_\alpha - \varphi_\beta)]\rangle$ and (right) $\Delta\langle\cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_2]\rangle$ in comparison with the Blast Wave model incorporating effects of LCC.

Blast Wave parameters of the LCC model used in Fig. 1 are tuned on the measured hadron spectra and the anisotropic flow at the LHC. The large charge dependent part of the correlation $\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$ can be reproduced well by this LCC model while it fails to describe the higher ($n > 1$) harmonic correlations. The right plot of Fig. 1 shows the charge dependent parts of the correlations $\langle\cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_2]\rangle$ in comparison with the LCC model calculations. Partial agreement between these measured correlations and the LCC model indicates that the "effective" LCC is indeed realized on the kinetic freeze-out surface. Therefore, the observed charge dependent part of the correlation $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP})\rangle$ ($m = -2$ in Fig. 1 (right)) can be interpreted mostly as the LCC induced correlation. More studies are needed to quantify the actual contributions from the effects of LCC in the CME studies. ALICE also measured a charge dependent part of the two particle correlation with respect to the 3rd and 4th order collision symmetry planes, which also may help in disentangling effects from LCC and CME [11, 12].

It was suggested in [5] that non-zero mixed harmonic correlations associated with the possible directed flow v_1 may be generated by the initial energy density fluctuations and hydrodynamic expansion of the system created in a heavy-ion collision. This effect may contribute a charge independent backgrounds for the CME search. Figure 2 shows the measured charge independent part of the correlations $\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$ (left) and $\langle\cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_2]\rangle$ (right). An estimate of the charge independent correlation with HIJING event generator in Fig. 2 (left) indicates large non-flow contribution to the charge independent part of the correlations $\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$ [13]. At the same time, a rough agreement between the data and AMPT model [14] supports the interpretation of the charge indepen-

dent correlations with respect to the 2nd order collision symmetry plane in terms of the event-by-event initial energy fluctuations. Further studies, in particular the comparison with the differential dependencies shown in Fig. 3 and in [15], are needed to make firm conclusions.

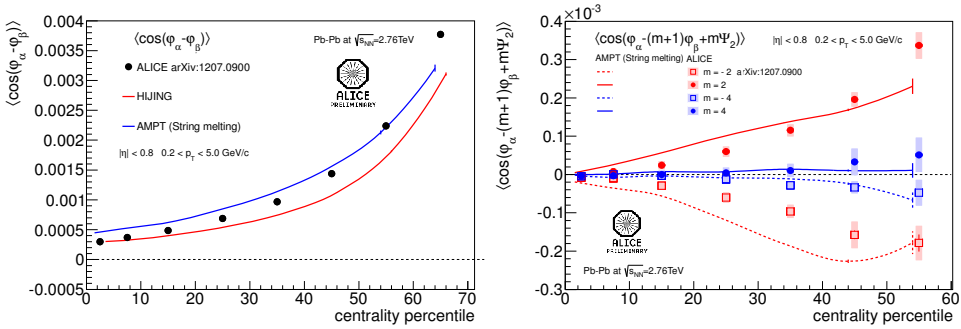

Fig. 2. Centrality dependence of the charge independent part of the correlation (left) $\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$ and (right) $\langle\cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_2]\rangle$ measured by ALICE in comparison with HIJING and AMPT with the *string melting* configuration [13, 14].

Differential studies of charged dependent correlations *versus* pair transverse momentum and pseudo-rapidity provide further constraints on models. Figure 3 shows the pair differential dependencies of the correlation $\langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_{\mathrm{RP}})\rangle$. Similarly to the results reported in [7] for the correlation $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\mathrm{RP}})\rangle$, we observe that the correlation is localized within about one unit of rapidity (or may even change sign as a function of $\Delta\eta$) and extends up to the higher p_{T} of the pair.

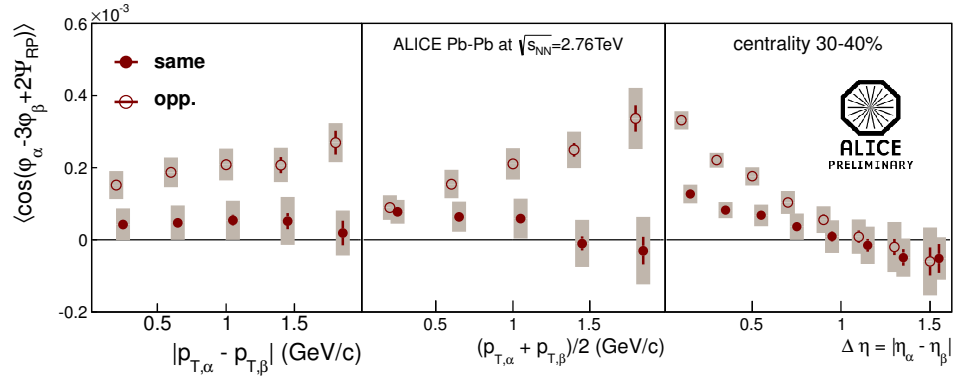

Fig. 3. The pair differential correlation $\langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_{\mathrm{RP}})\rangle$ as a function of (left) the transverse momentum difference $|p_{\mathrm{T},\alpha} - p_{\mathrm{T},\beta}|$, (center) the average transverse momentum $(p_{\mathrm{T},\alpha} + p_{\mathrm{T},\beta})/2$, (right) the rapidity separation $\Delta\eta = |\eta_\alpha - \eta_\beta|$ of the charged particle pair.

4. Summary

Charge dependent azimuthal correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV were measured by the ALICE Collaboration. A significant non-zero correlation $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP})\rangle$ was observed, which was originally proposed as an observable sensitive to the CME and thus to effects from local parity violation in QCD. The experimental analysis was extended to the higher moments of the two particle azimuthal correlations $\langle\cos[n(\varphi_\alpha - \varphi_\beta)]\rangle$ for $n = 1$–4 and to the mixed harmonic charge dependent azimuthal correlations with respect to the 2nd order collision symmetry plane (*e.g.* $\langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_2)\rangle$). These new results provide an important experimental input which is relevant to CME, "effective" LCC on the kinetic freeze-out, and directed flow fluctuations.

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