Charge dependence of identified two-hadron correlation relative to the reaction plane in Pb-Pb collisions measured with ALICE

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Abstract. Recently a non-zero charge dependence of two-particle correlation relative to the reaction plane in relativistic heavy-ion collisions was observed by RHIC and LHC experiments. The interpretation of these results is a hot topic of debate in the heavy-ion community because of its possible implication for our understanding of parity violation in strong interactions. We extend the ALICE measurement of the charge dependent two-particle correlation in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV with one identified hadron (pion, kaon, or proton). Correlations are reported as a function of the identified hadron transverse momentum. These new results are important for disentangling contributions from a number of competing physics effects, such as local charge conservation coupled with strong anisotropic flow, flow fluctuations, and possible contribution from parity violation coupled with strong magnetic fields, the so-called chiral magnetic effect.

1. Introduction

Heavy ion collisions offer an opportunity to study possible parity violation in interactions between quarks. The magnitude of global parity violation in strong interactions is constrained to a very small value through measurements of the neutron electric dipole moment [1,2]. On a local scale, parity symmetry can be spontaneously broken via QCD transitions known as instantons and sphalerons [3]. In small regions with non-zero topological charge, these interactions can couple to quarks, leading to a change of chirality and a violation of P- and CP-symmetry. It has been suggested that in the presence of a strong magnetic field, such as generated in a heavy-ion collision, the spin and momentum of produced quarks align with the field lines. In combination with the parity violating effects described above this results in a charge separation relative to the reaction plane called the Chiral Magnetic Effect (CME). This can, in principle, be measured in existing relativistic heavy-ion experiments [4].

One of the main observables to probe the charge separation effect, as proposed by Voloshin [5], is a two particle correlation relative to the reaction plane,

$$c_{\alpha\beta} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\rm RP}) \rangle, \qquad (1)$$

where φ denotes the azimuthal angle, α, β the electric charges of two correlated particles and $\Psi_{\rm RP}$ the reaction plane angle. The reaction plane, which is defined by the impact-parameter vector and the beam direction, is oriented on average perpendicular to the magnetic field. The angular brackets denote the average over all pairs in all collisions. The parity-even correlation in Eq. 1 is sensitive to parity-odd symmetry breaking while cancelling out background sources independent to the reaction plane. This correlation has been extensively studied at RHIC and LHC [6–9], where a significant charge separation was observed. The interpretation of these results is subject to discussion, because various physical reaction plane dependent sources other than CME are likely to contribute to the observed correlation, like local charge conservation and flow fluctuations [10–12]. It is therefore important to develop not only a qualitative but a quantitative understanding of the contributing sources through additional measurements and detailed model calculations. Correlations with identified particles help to elucidate the effect of different particle properties on the charge dependent correlation. Local charge conservation may contribute to the observed charge seperation through modulation by elliptic flow, making it reaction plane dependent. Blast-wave fits have shown that this can explain a significant fraction of the measured correlations [13]. In this case, correlations with identified particles that exhibit different elliptic flow [14] are expected to have a different charge correlation. The focus of this study is the correlation

$$c^{ij}_{\alpha\beta}(p_{\rm T}) = \langle \cos(\varphi^i_\alpha(p_{\rm T}) + \varphi^j_\beta - 2\Psi_{\rm RP})\rangle, \quad (2)$$

where i is a charged pion, kaon or proton and j is an unidentified charged hadron. The observable is studied as a function of $p_{\rm T}$, the transverse momentum of the identified hadron.

2. Analysis details

Around 12 million minimum bias Pb-Pb events at $\sqrt{s_{\rm NN}} = 2.76$ TeV from the 2010 LHC run, collected by the ALICE detector, were analyzed. Details on the ALICE detector and collision trigger can be found in [15]. Tracks reconstructed with the Time Projection Chamber (TPC) in the kinematic range of $0.2 < p_{\rm T} < 5.0$ GeV/c and $|\eta| < 0.8$ are used for the analysis. Particles are identified with the method described in [14] using energy loss in the TPC (dE/dx) and the speed measurement (β) in the Time of Flight detector. The orientation of the reaction plane is estimated with the second order event plane angle $\Psi_{\rm EP,2}$. The measured correlation relative to the event plane is corrected for the event plane resolution [16]:

$$c^{ij}_{\alpha\beta}(p_{\rm T})\{\rm EP\} = \langle \cos(\varphi^i_\alpha(p_{\rm T}) + \varphi^j_\beta - 2\Psi_{\rm EP,2})\rangle / R_2. \quad (3)$$

The event plane is estimated with the V0-A and V0-C forward multiplicity detectors which respectively cover the pseudo-rapidity region $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. After applying recentering corrections to the event plane measurement, the 3-subevent method is employed to extract the resolution correction factor R_2 [16]:

$$R^A_2 = \sqrt{\frac{\langle \cos 2(\Psi^A_{\rm EP,2} - \Psi^B_{\rm EP,2})\rangle \langle \cos 2(\Psi^A_{\rm EP,2} - \Psi^C_{\rm EP,2})\rangle}{\langle \cos 2(\Psi^B_{\rm EP,2} - \Psi^C_{\rm EP,2})\rangle}}. \quad (4)$$

In Fig. 1 the resolution correction factor is shown versus collision centrality for a number of ALICE subdetectors. For different limits of the resolution correction, the estimated elliptic flow is [17, 18]

$$v_2\{\rm EP\} = \begin{cases} \langle v_2 \rangle, & \text{for } R_2 \to 1 \\ \sqrt{\langle v_2^2 \rangle}, & \text{for } R_2 \to 0 \end{cases}. \quad (5)$$

Because of flow fluctuations, the estimate of v_2 with the event plane method can significantly differ depending on the event plane resolution correction. The right side of Fig. 1 shows that

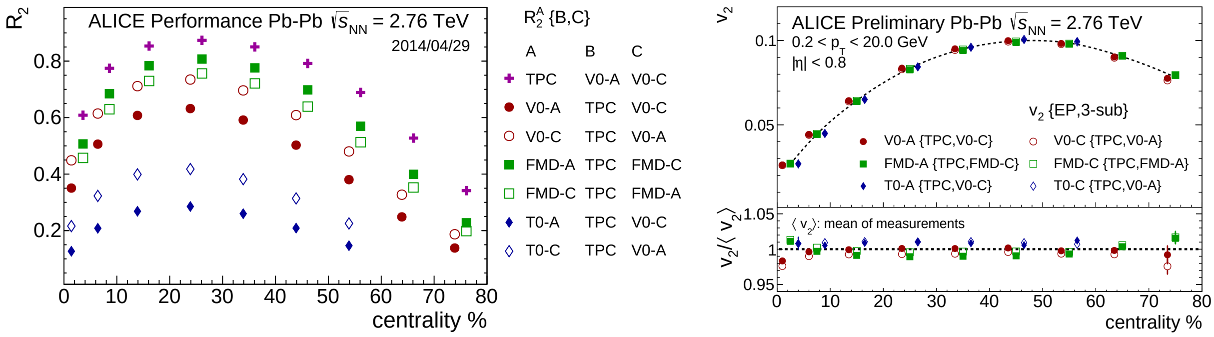

Figure 1. (left) Second order event plane resolution correction factor R_2 for the TPC, V0-A/C, FMD-A/C and T0-A/C subdetectors estimated with the 3-subevent method. (right) Estimation of $v_2\{\text{EP}\}$ with six different event plane estimators.

measurements of v_2 with different estimations from ALICE subdetectors are consistent within $\sim 4\%$ [19], and the ordering of the magnitude of the v_2 measurements is consistent with Eq. 5. The two particle correlation in Eq. 2 is measured with respect to V0-A and V0-C event plane estimates in 10% centrality bins. For the final result the two event plane measurements were combined, as well as the 10% centrality ranges to a 10-30% and 30-50% centrality range.

3. Results

In Fig. 2 the correlation Eq. 2 is shown for the 10-30% and 30-50% centrality range. The different charge combinations of correlated particle pairs are combined in $\alpha = \beta$ (same) and $\alpha = -\beta$ (opp.) charge pairs. For the proton correlation at $p_{\mathrm{T}} < 1$ GeV/c only anti-protons are used in order to avoid contamination from knock-out protons from detector material. The trends for hadron, pion, kaon and proton correlations for like-sign and unlike-sign are similar in both centrality ranges, while the magnitude of the observed correlations are approximately three times stronger in more peripheral collisions. A clear particle species dependence is observed in the unlike-sign correlations, which is close to zero for pions, but increases towards negative

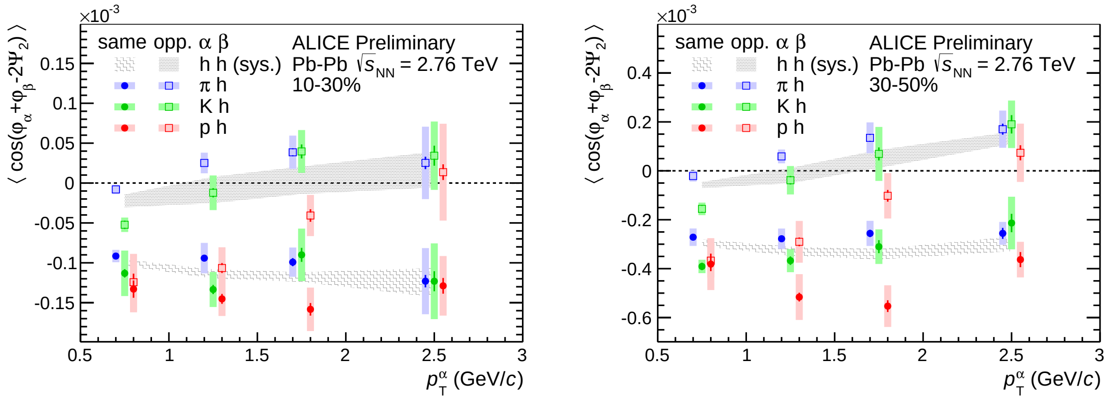

Figure 2. Results for $c^{ij}_{\alpha\beta}$ defined by Eq. 2 in the 10-30% (left) and the 30-50% (right) centrality range. The fine hatched areas show the unlike-sign hadron correlation and the coarse hatched areas the like-sign hadron correlation. The unlike-sign correlations for identified hadrons are shown in open squares, and the like-sign correlations in full squares. Pions are shown in blue, kaons in green, and protons in red. The systemetic error is indicated with the colored bands.

values at low transverse momentum for kaons and protons. The like-sign correlations do not have a significant slope as a function of p_{T}. Although an ordering appears from pions to protons in the magnitude of the correlations, the differences are not significant as for the unlike-sign correlations.
Several checks are made to evaluate the systematic uncertainty of the measurement. Two track reconstruction approaches, using TPC standalone and a combined TPC and Inner Tracking System information, are considered. Requirements on the track reconstruction quality and particle identification efficiency and purity were studied similar to [14]. The effect of magnet polarity, which determines the direction of curvature for charged particles, was checked for both configurations, as well as individual charge combinations (++,--,+-,-+). Residual effects from detector non-uniformity were checked by replacing the cosine in Eq. 2 by a sine, and different event plane estimators (V0-A/C, FMD-A/C). All contribute significantly to the final systematic uncertainty, which has been calculated for each p_{T} bin with deviations of the mentioned systematic checks added in quadrature. In the intermediate p_{T} region the total relative systemetic uncertainty is around 5% for unindentified hadron correlations and 20% for the correlations with an identified hadron. Finally a weigthed average was made of the identified particle correlations using identified particle spectra and demonstrated consistency with the unidentified hadron correlation.

4. Summary
In this study a new charge-dependent measurement with identified particles is presented. The charge-dependent correlation $\langle\cos(\varphi^{i}_{\alpha}(p_{\mathrm{T}}) + \varphi^{j}_{\beta} - 2\Psi_{\mathrm{RP}})\rangle$ (Eq. 2) is measured with a charged pion, kaon or proton (i) and an unidentified charged hadron (j). In the opposite sign correlations a significant dependence on particle species is observed at low p_{T}. This new result signals that effects contributing to the previously observed charge separation with unidentified hadrons have a different contribution depending on particle species. Model calculations, in particular of the local charge conservation with identified particles, and further measurements are required to quantify and describe the observed charge separation effects, and achieve a detailed understanding of the charge-dependent correlations and possible contributions from CME.

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