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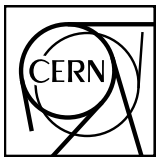

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Charge separation relative to the reaction plane in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The ALICE Collaboration*

Abstract

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 pseudo–rapidity range $|\eta| < 0.8$ are presented as a function of the collision centrality, particle separation in pseudo–rapidity, and transverse momentum. A clear signal of 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. Models incorporating effects of local parity violation in strong interactions fail to describe the observed collision energy dependence.

*See Appendix A for the list of collaboration members

The possibility to observe parity violation in the strong interaction using relativistic heavy–ion collisions has been discussed for many years [1, 2, 3]. In quantum chromodynamics (QCD), this symmetry violation originates in the interaction between quarks and topologically non–trivial gluonic fields, instantons, and sphalerons [4]. This interaction, which is characterised by the topological charge, breaks the balance between the number of quarks with different chirality, resulting in a violation of the *P*- and *CP*-symmetry. The experimental search has intensified recently, following the realisation [5] that under the influence of the strong magnetic field which is generated by the colliding nuclei a charge separation along the direction of this 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), could be produced. This phenomenon is called the Chiral Magnetic Effect (CME). Due to fluctuations in the sign of the topological charge, the resulting charge separation averaged over many events is zero. This makes the observation of the CME possible only via *P*–even observables, expressed in terms of two– and multi–particle correlations. The previous measurement of charge separation by the STAR Collaboration [6] is consistent with the qualitative expectations for the CME, and has triggered an intense discussion [9, 7, 8, 10]. In this Letter we report the measurement of the charge–dependent azimuthal correlations at mid–rapidity in Pb–Pb collisions at the centre 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, which is usually quantified by the anisotropic flow coefficients, v_n, in a Fourier decomposition [11]. Local violation of parity symmetry results in the additional P–odd sinus terms [3, 12, 6]:

$$\frac{dN}{d\phi_\alpha} \sim 1 + \sum_n \left[\mathrm{v}_{n,\alpha} \cos(n\Delta\phi_\alpha) + a_{n,\alpha} \sin(n\Delta\phi_\alpha)\right], \tag{1}$$

where $\Delta\phi_\alpha = \phi_\alpha - \Psi_{\mathrm{RP}}$ is the azimuthal angle ϕ_α of the particle of type α relative to the reaction plane angle, Ψ_{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 multi–particle correlator [12] which probes the magnitude of the a_1 coefficient, and at the same time suppresses the background correlations unrelated to the reaction plane:

$$\begin{aligned} \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle &= \left\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \right\rangle \\ &- \left\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \right\rangle. \end{aligned} \tag{2}$$

The brackets denote an average over the particle pairs within the event as well as an average over the analysed 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 $\left\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \right\rangle$ and $\left\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \right\rangle$ quantify the correlations in– and out–of plane, respectively. The latter one is sensitive to the charge correlations resulting from the CME: $\left\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \right\rangle \sim \langle a_{1,\alpha} a_{1,\beta} \rangle$. Recent calculations [13] suggest that Eq. 2 may have a negative (i.e. out–of–plane), charge independent, dipole flow contribution originating from fluctuations in the initial condition of a heavy–ion collision. The construction of the correlator in Eq. 2 as the difference between these two contributions suppresses correlations not related to the reaction plane orientation. In order to evaluate each of the two terms in Eq. 2, we also measure the two particle correlator:

$$\begin{aligned} \langle \cos(\phi_\alpha - \phi_\beta) \rangle &= \left\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \right\rangle \\ &+ \left\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \right\rangle, \end{aligned} \tag{3}$$

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, $\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle$ and $\langle \sin\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle$, which is important for detailed comparisons with model calculations.

A description of the ALICE detector and its performance can be found in [14, 15]. For this analysis, the following detector subsystems were used: the Time Projection Chamber (TPC) [16], the Silicon Pixel Detector (SPD), two forward scintillator arrays (VZERO), and two Zero Degree Calorimeters (ZDC) [14]. The TPC is the main tracking detector, providing full azimuthal coverage in the pseudo–rapidity range $|\eta| < 0.9$. The SPD used in the trigger logic and in the centrality determination, provides high spatial resolution near the primary vertex. The VZERO detectors cover the pseudo–rapidity ranges between $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. The ZDCs are located 114 m on either side from the nominal interaction point and are sensitive to the distribution of neutrons near beam rapidity.

This analysis uses a sample of about 13 million minimum–bias trigger events of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, which were collected with the ALICE detector during the first LHC heavy–ion run in 2010. The standard ALICE offline event selection criteria [17] 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 [14]. Higher amplitude, and hence higher particle multiplicity, corresponds to more central (smaller impact parameter) events. 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 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. Accepted tracks were required to have at least 80 out of 159 possible space points measured in the TPC, and an average χ^2 per degree of freedom of the momentum fit to be below 2 per TPC cluster. To select tracks which originate from the primary collision vertex, a cut of 3 cm on the distance of closest approach (dca) in the transverse plane and the longitudinal direction between the track and reconstructed primary vertex was applied.

To evaluate the systematic uncertainties in the analysis, events recorded with two different magnetic field polarities were analysed leading to an uncertainty below 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 tracks that do not originate from the collision vertex was estimated by varying the dca cut from 2 cm to 4 cm, in steps of 0.5 cm, and was calculated to be below 15%. Effects due to non–uniform 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 analysis [17], which are affected in different ways by non–flow 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 ranges from 9% for the 20–30% centrality, and 18% (24%) for the 50–60% (60–70%) centrality class. Finally, the differences in the results from the four independent analysis methods, that are going to be discussed later in the text, 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}.

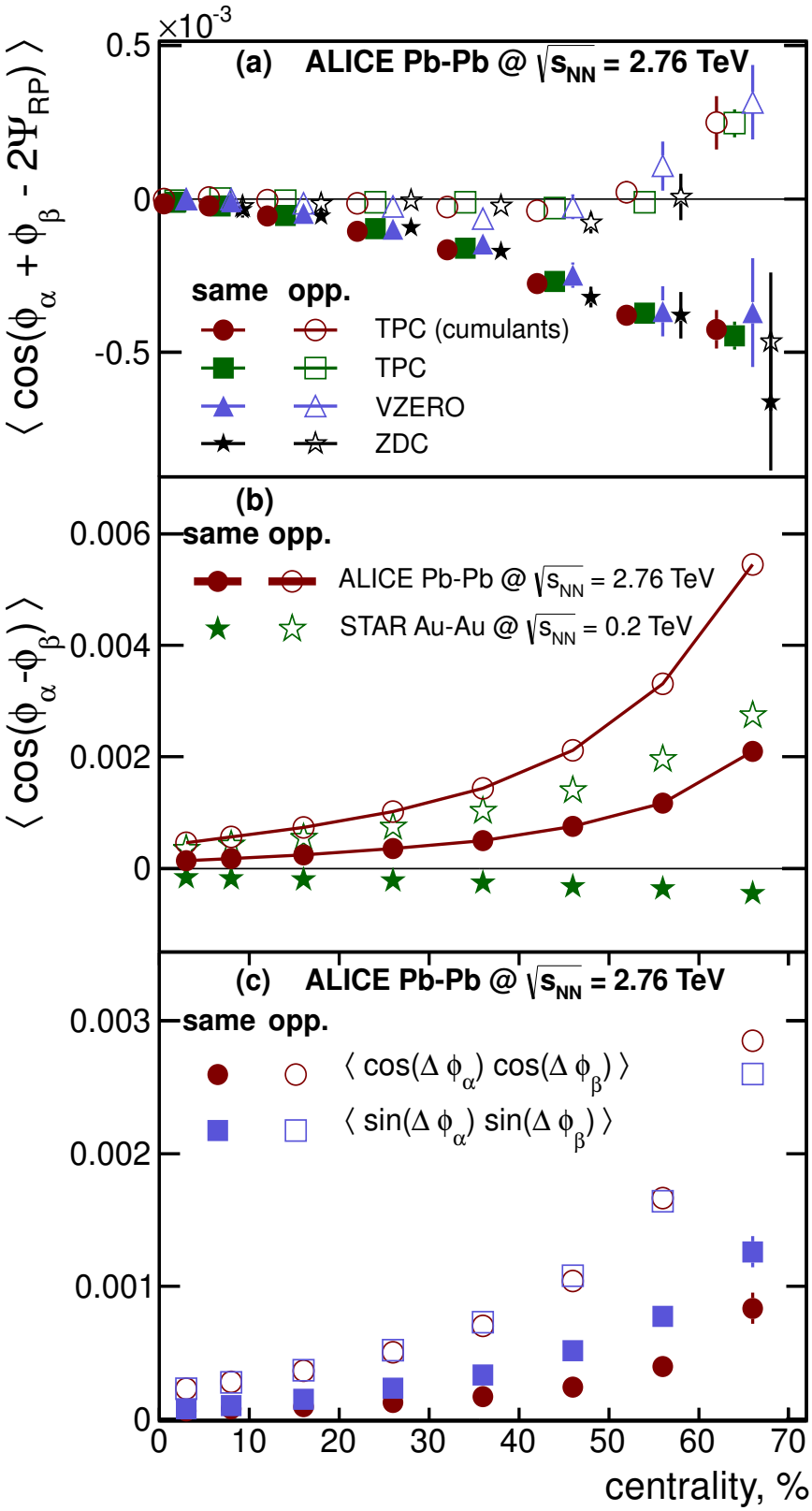

Fig. 1: (Colour online) (a) Centrality dependence of the correlator defined in Eq. 2 measured with the cumulant method, and from correlations with the reaction plane estimated using the TPC, the ZDC and the VZERO detectors. Only statistical errors are shown. The points are displaced slightly in the horizontal direction for visibility. (b) Centrality dependence of the two–particle correlator defined in Eq. 3 compared to the STAR data [6]. The width of the solid red lines indicates the systematic uncertainty of the ALICE measurement. (c) Decomposition of the correlators into $\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle$ and $\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$ terms.

Figure 1a 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, labelled *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 [18], 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 [19]. The small differences between the methods are considered as part of the systematic uncertainty.

Figure 1b shows the centrality dependence of the two–particle correlator $\langle\cos(\phi_\alpha - \phi_\beta)\rangle$, as defined in Eq. 3. 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 results differ from those reported by the STAR Collaboration for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [6] for which a negative correlations are observed for the same charged pairs.

Figure 1c shows the $\left\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \right\rangle$ and $\left\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \right\rangle$ terms separately. For pairs of the same charge particles, we observe that the correlations projected onto the direction perpendicular to the reaction plane, $\left\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \right\rangle$, are larger than those projected onto the reaction plane direction, $\left\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \right\rangle$. On the other hand, for pairs of opposite charge, the two terms are almost identical except for the most peripheral collisions.

Figure 2 presents the three–particle correlator $\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle$ as a function of the collision centrality compared to model calculations and results for RHIC energies. The statistical uncertainties are represented by the error 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 [6]. 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 is compared to the expectations from the HIJING model [20]. The HIJING results do not exhibit any significant difference between the correlations of pairs with same and opposite charge and 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 [6].

For the correlations originating in CME, the correlation of pairs with same and opposite charge should be similar in magnitude and opposite in sign. The results from ALICE in Fig. 2 show a strong correlation of pairs with the same charge and simultaneously a very weak correlation for the pairs of opposite charge. This could be interpreted as "quenching" of the charge correlations for the case when one of the particles is emitted toward the centre of the dense medium created in a heavy–ion collision [5]. An alternative explanation can be provided by a recent suggestion [13] 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 [13] appear to be very close to the measurement. Our results for charge independent correlations are given by the blue band in Fig. 2.

The thick solid line in Fig. 2 shows a prediction [21] for the same sign correlations due to the CME at LHC energies. The model makes no prediction of 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 the correlations by about a factor of five from RHIC to LHC, which would significantly underestimate the observed magnitude of the same sign correlations seen at the LHC. At

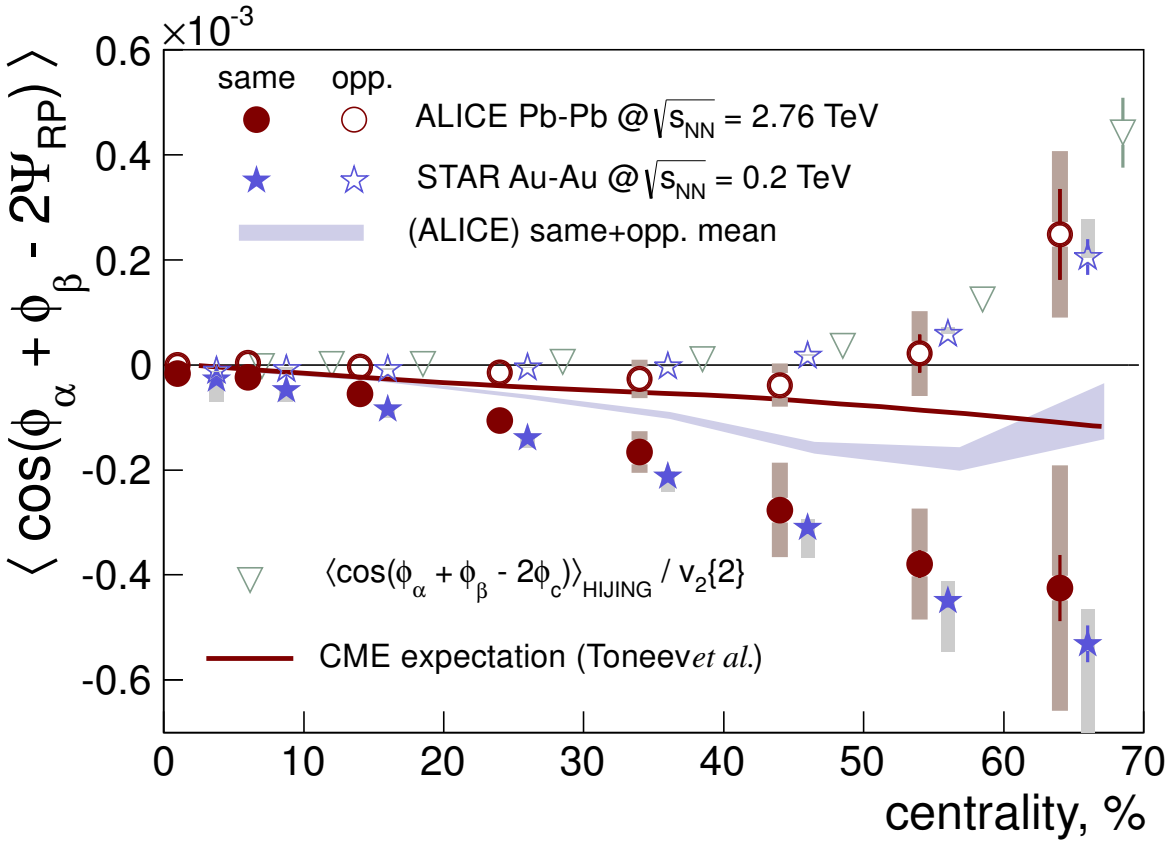

Fig. 2: (colour online) The centrality dependence of the three–particle correlator defined in Eq. 2. The red circles indicate the ALICE results obtained from the cumulant analysis. The blue stars show the STAR data from [6]. The green triangles represent the genuine three–particle correlations ($\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle$) from HIJING [20] corrected for the experimentally measured $v_2\{2\}$ [17]. A model prediction for the same sign correlations incorporating the Chiral Magnetic Effect for LHC energies [21] is shown by the solid red line. Points are displaced horizontally for visibility.

the same time in [5, 10], it was suggested that the CME might have the same magnitude at the LHC and at RHIC energies. Note that, in [8] it is argued that local charge conservation effects may be responsible for a significant part of the observed charge dependence of the correlator $\langle\cos(\phi_\alpha+\phi_\beta-2\Psi_{RP})\rangle$. A full discussion of these effects is beyond the scope of this paper, and will be presented in a future publication.

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 rapidity 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 pseudo–rapidity difference, while there is a dependence on the transverse momentum. The pairs of the same charge show a stronger dependence and a different pattern: the magnitude of the correlation increases with increasing average p_t of the charged particle pair and the correlation has a width of about one unit in pseudo–rapidity. The results on the p_t difference indicate no significant contribution from short range correlations (e.g. HBT).

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 difference in the correlation strength between the same and opposite charge particle combinations is observed. The three–particle correlation observed by the ALICE Collaboration shows little energy dependence when compared to the results from RHIC for Au–Au collisions at $\sqrt{s_{NN}}=0.2$ TeV.

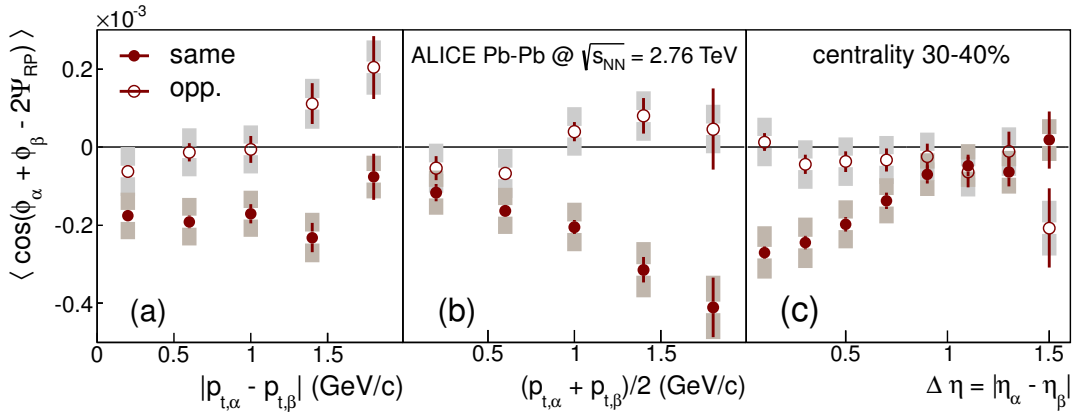

Fig. 3: (Colour online) The three–particle correlator defined in Eq. 2 as a function of (a) the transverse momentum difference, $|p_{\mathrm{t},\alpha} - p_{\mathrm{t},\beta}|$, (b) the average transverse momentum, $(p_{\mathrm{t},\alpha} + p_{\mathrm{t},\beta})/2$, and (c) the rapidity separation, $|\eta_\alpha - \eta_\beta|$, of the charged particle pair.

The two–particle correlation measured by ALICE differs strongly from those observed by the STAR Collaboration at RHIC. Analyses of higher harmonic correlations are planned and may yield a better understanding of the complex charge dependent correlations seen at the LHC energies.

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