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Searches for Chiral Magnetic Effect and Chiral Magnetic Wave in Xe–Xe and Pb–Pb collisions with ALICE

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ABSTRACT

An important property of the strong interaction which is potentially observable in heavy-ion collisions is local parity violation. It manifests as a charge separation along the direction of the magnetic field, a phenomenon called the Chiral Magnetic Effect (CME). A similar effect in which the presence of a vector charge (e.g., electric charge) causes a separation of chiralities is the Chiral Separation Effect (CSE). Their coupling leads to a wave propagation of the electric charge called the Chiral Magnetic Wave (CMW), causing a charge-dependent anisotropic flow.

The charge dependence of the three-particle correlator $\gamma_{\rm ab}$, often employed as evidence for the CME, is measured in Xe–Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV. This correlator depends strongly on centrality and is similar to that in Pb–Pb collisions. This finding and the prediction of a significantly larger CME signal in Pb–Pb than Xe–Xe collisions from Monte Carlo calculations including a magnetic field due to spectators point to a large non-CME contribution to the correlator. Furthermore, it is reproduced by the Anomalous Viscous Fluid Dynamics model with values of the CME signal close to zero and by a blast wave model calculation that incorporates background effects. The charge dependence of elliptic (v_2) and triangular (v_3) flow coefficients of unidentified charged hadrons and pions are used to search for the CMW in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The v_3 results are consistent with those of v_2, which suggests a significant background contribution.

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PoS(PANIC2021)364

1. Introduction

The main goal of ultrarelativistic heavy-ion collisions is to study the high-temperature phase predicted by quantum chromodynamics, the quark–gluon plasma (QGP). A key observable for the characterization of the properties and evolution of the QGP is anisotropic flow. It arises from the asymmetry in the initial geometry of the collision combined with the initial inhomogeneities of the system's energy density. The magnitude of the anisotropic flow is quantified by the v_n coefficients in a Fourier decomposition of the particle azimuthal distribution with respect to the collision symmetry plane Ψ_n [1]. The second (v_2) and third (v_3) flow coefficients are called elliptic and triangular flow, respectively. Elliptic flow is the largest contribution to the asymmetry of non-central collisions because of the almond-like geometry of the interaction volume.

In the last decade, heavy-ion collisions have been proposed as a tool to investigate local parity violation in strong interactions. The parity violation in strong interactions might occur in microscopic domains due to the existence of topologically non–trivial configurations of the gluonic field. The interactions between quarks and these gluonic fields change the quark chirality, breaking parity symmetry by creating an imbalance between the number of left- and right-handed quarks. This chiral asymmetry coupled with the strong magnetic field produced by colliding ions [2] leads to a charge separation along the direction of the magnetic field, a phenomenon called Chiral Magnetic Effect (CME) [2]. The observation of the CME is experimentally difficult and possible only via azimuthal particle correlations since the charge separation averaged over many events is zero. This introduces a large flow-related background into the measurements with the most significant background source being the local charge conservation (LCC) coupled with elliptic flow [3]. The three-particle correlator $\gamma_{\rm ab} \equiv \langle \cos(\varphi_{\rm a} + \varphi_{\rm b} - 2\Psi_2)\rangle$ [4] (a and b denote the charge) has been proposed to measure the CME since it suppresses background contributions at the level of v_2.

Another effect in which the presence of a vector charge (e.g. electric charge) causes a separation of chiralities is the Chiral Separation Effect (CSE) [5]. The combination of CME and CSE leads to a wave propagation of the electric charge, the Chiral Magnetic Wave (CMW) [6]. According to theory [6], the elliptic flow becomes charge dependent due to the CMW and can be written as

$$v_2^{\pm} \approx \langle v_2 \rangle \mp rA/2, \tag{1}$$

where $\langle v_2\rangle = (v_2^+ + v_2^-)/2$, $A = (N^+ - N^-)/(N^+ + N^-)$ is the charge asymmetry (with N^+ and N^- the number of positive and negative charged hadrons, respectively), and the slope r encodes the strength of the electric quadrupole due to the CMW. This allows one to write $\Delta v_2 = v_2^- - v_2^+ \approx rA$. By measuring Δv_2 as a function of A, it is possible to extract r directly. However, the interpretation of the experimental results is complicated by background contributions associated with LCC. Therefore it was proposed to use as observable the normalized slope, $r^{\rm Norm}_{\Delta v_2} = {\rm d}(\Delta v_2/\langle v_2\rangle)/{\rm d}A$ [7].

In these proceedings, the measurements of three-particle correlator $\gamma_{\rm ab}$ in Xe–Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV are presented. They are compared with published results from Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [8] and calculations from Anomalous Viscous Fluid Dynamics (AVFD) model [9] and from a blast wave (BW) parametrization that incorporates background effects. In addition, the normalized slopes of unidentified charged hadrons and pions measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV are reported.

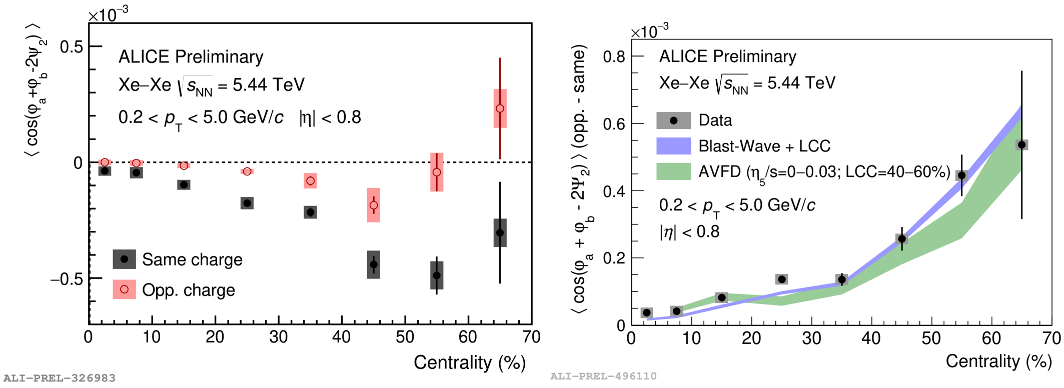

Figure 1: Left: centrality dependence of $\gamma_{\rm ab}$ correlator for pairs of particles with same (black markers) and opposite (red markers) charge from Xe–Xe collisions at $\sqrt{s_{\rm NN}}$ = 5.44 TeV. Right: centrality dependence of the difference between opposite and same charge pair correlations for $\gamma_{\rm ab}$ compared to model calculations: BW parametrization coupled with LCC effects (blue curve) and AVFD model [9] (green curve). Bars (boxes) denote statistical (systematic) uncertainties.

2. Analysis details

The data recorded by ALICE [10] during the 2015 Pb–Pb and 2017 Xe–Xe runs are used in this analysis. The Inner Tracking System (ITS) and the Time Projection Chamber (TPC) are employed to reconstruct charged-particle tracks and to measure their momenta. The V0 detector, which covers the pseudorapidity ranges $-3.7 < \eta < -1.7$ (V0C) and $2.8 < \eta < 5.1$ (V0A), is used for triggering, event selection, and the determination of centrality and Ψ_2. Approximately 1×10^6 Xe–Xe and 60×10^6 Pb–Pb events with a primary vertex position within ±10 cm from the nominal interaction point along the beam line are selected. Charged particles reconstructed using the combined information from the ITS and TPC in $|\eta| < 0.8$ are selected with full azimuthal coverage. Only tracks with a transverse momentum ($p_{\rm T}$) within $0.2 < p_{\rm T} < 5.0$ GeV/c and $0.2 < p_{\rm T} < 1.0$ GeV/c are employed in the CME and CMW analyses, respectively. For the CMW analysis, the identification of $\pi^{\pm}$ is performed based on the specific energy loss measured in the TPC within $0.2 < p_{\rm T} < 0.5$ GeV/c. The event charge asymmetry is estimated using unidentified charged hadrons with $0.2 < p_{\rm T} < 10.0$ GeV/c. The flow coefficients are measured employing the Q-cumulant method [11] with a gap in pseudorapidity of 0.4 to suppress non-flow contributions (i.e. short-range correlations unrelated to the azimuthal asymmetry in the initial geometry).

3. Results

The left panel of Fig. 1 shows the $\gamma_{\rm ab}$ correlator for same and opposite charge pairs as a function of centrality. The magnitude of same charge pair correlations decreases from central to peripheral collisions, while it is close to zero within uncertainties for opposite charge pairs. This stronger correlation of same charge pairs compared to opposite charge pairs is compatible with a charge separation as expected in the presence of the CME.

The charge separation is investigated using the difference between opposite and same charge pair correlations $\Delta\gamma_{\rm ab} \equiv \gamma_{\rm ab}^{\rm opp.} - \gamma_{\rm ab}^{\rm same}$. This difference compared with calculations from a BW

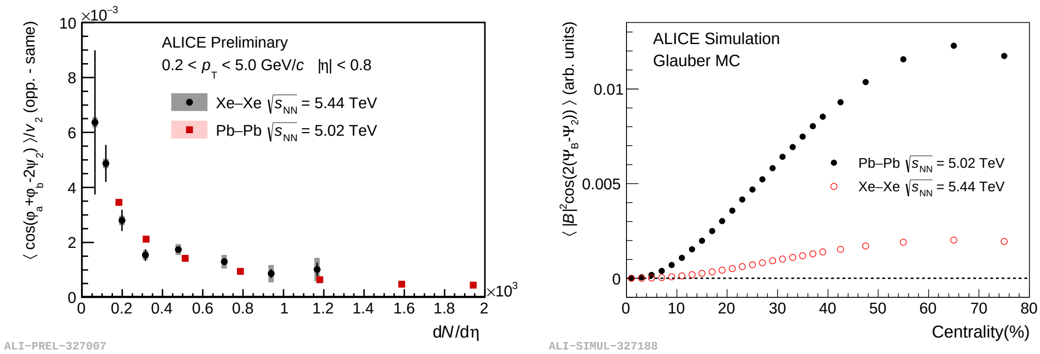

Figure 2: Left: difference between opposite and same charge pair correlations for γ_{ab} divided by v_2 as a function of charged-particle density in Xe–Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV compared to results from Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Bars (boxes) denote statistical (systematic) uncertainties. Right: the expected CME signal as function of centrality from MC Glauber simulations for Xe–Xe and Pb–Pb collisions.

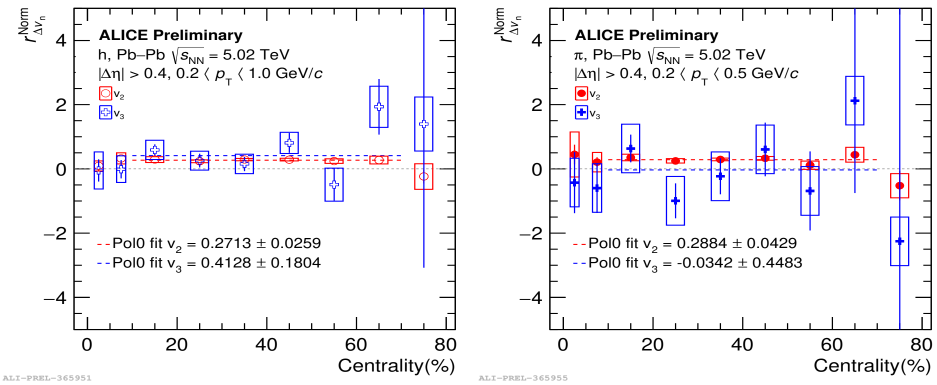

Figure 3: Centrality dependence of the normalized slopes $r^{\rm Norm}_{\Delta v_2}$ and $r^{\rm Norm}_{\Delta v_3}$ for unidentified charged hadrons (left) and pions (right) in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

parametrization coupled with LCC effects and from the AVFD model [9] is reported in the right panel of Fig. 1. The parameters of the BW model are tuned to describe the p_T spectra and the p_T-differential v_2 values of $\pi^{\pm}$, $K^{\pm}$, and p+$\overline{\rm p}$. The AVFD model is first calibrated to describe the centrality dependence of both the charged-particle density and elliptic flow. Then the dependence of $\Delta\gamma_{ab}$ on both the CME signal and the background is determined. The extracted values of the axial current density n_5/s, which control the initial chirality imbalance reflected into the CME signal, are consistent with zero within uncertainties [12]. Both models describe fairly well the measured data points for all centralities, indicating a dominant background contribution to γ_{ab}.

A comparison between $\Delta\gamma_{ab}$ divided by v_2 and that measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [8] is presented as a function of charged-particle density in the left panel of Fig. 2. The difference is positive for all centralities and its magnitude increases from central to peripheral collisions. A good agreement is found between Xe–Xe and Pb–Pb results within uncertainties. Furthermore, the expected centrality dependence of the CME signal in the two systems is evaluated with the help of Monte Carlo Glauber calculations including a magnetic field. The right panel of Fig. 2 shows the centrality dependence of the expected CME signal contribution in γ_{ab} for Xe–Xe and Pb–Pb collisions. The CME signal is weaker in Xe–Xe than Pb–Pb collisions in a given centrality interval. This finding coupled with the agreement of $\Delta\gamma_{\mathrm{ab}}$ between the two systems points to a large background contribution to γ_{ab} in Xe–Xe collisions.

Figure 3 presents the centrality dependence of the normalized slopes $r^{\mathrm{Norm}}_{\Delta v_2}$ and $r^{\mathrm{Norm}}_{\Delta v_3}$ of unidentified charged hadrons (left) and pions (right) in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. The $r^{\mathrm{Norm}}_{\Delta v_2}$ and $r^{\mathrm{Norm}}_{\Delta v_3}$ have similar magnitude within uncertainties, suggesting a large non-CMW contribution to the charge-dependent anisotropic flow.

4. Summary

The charge-dependent three-particle correlator γ_{ab} has been measured in Xe–Xe collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.44 TeV. Its charge dependence, $\Delta\gamma_{\mathrm{ab}}$, increases from central to peripheral collisions and is similar to that from Pb–Pb collisions. Monte Carlo Glauber simulations predict a smaller magnitude of the CME signal in Xe–Xe than Pb–Pb collisions which coupled with the agreement of $\Delta\gamma_{\mathrm{ab}}$ between the two systems implies that the dominant contribution to γ_{ab} is due to background effects in Xe–Xe collisions. This is further supported by the comparison with a BW parametrization that incorporates LCC effects and by AVFD calculations with values of the CME signal consistent with zero. In addition, the normalized slopes $r^{\mathrm{Norm}}_{\Delta v_2}$ and $r^{\mathrm{Norm}}_{\Delta v_3}$ of unidentified charged hadrons and pions have been measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. These slopes have similar magnitude within large uncertainties, which points to a significant background contribution.

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PoS(PANIC2021)364