Collective behavior of hyperons in Pb-Pb collisions with ALICE

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Hyperons created in non-central nucleus-nucleus collisions possess collective behavior known as elliptic flow (v_2). Also, hyperons are sensitive to the magnetic field and vorticity of the produced system resulting in their polarization. The measurement of elliptic flow and the polarization of Λ and Ξ^- hyperons in Pb–Pb collisions, performed with the ALICE detector at the LHC are presented.

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1. Elliptic flow

The system created in high-energy nuclear collisions behaves differently in overlapping and peripherial regions [?], see Fig. ??. Particle flow from the overlapping region signals the presence of multiple interactions between the constituents of the medium created in the collision. Flow is measured from the observation of anisotropic flow which is the anisotropy in particle momentum distributions correlated with the reaction plane. The reaction plane is defined by the impact parameter and the beam direction z, see Fig. ??. Flow is determined as

$$E\frac{\mathrm{d}^3\mathrm{N}}{\mathrm{dp}^3} = \frac{1}{2\pi}\frac{\mathrm{d}^2\mathrm{N}}{p_\mathrm{T}p_\mathrm{T}\mathrm{d}\eta}\{1 + 2\sum_{n=1}^{\infty} v_n(p_\mathrm{T},\eta)\cos[n(\phi - \Psi_n)]\},$$

where $E, N, p, p_\mathrm{T}, \phi$ and η are the energy, yield, momentum, transverse momentum, azimuthal angle, and pseudorapidity of particles, respectively, and Ψ_n is the azimuthal angle of the symmetry plane of order n. The v_n coefficients are given by

$$v_n = \langle cos[n(\phi - \Psi_n)]\rangle,$$

where $\langle\rangle$ denote an average over all particles in a single event. The second order coefficient, v_2, appears to be the largest since the momentum anisotropy typically develops in the overlapping region in the plane perpendicular to the beam direction.

The transverse momentum differential v_2 is presented in Fig. ?? [?]. The agreement of the calculations of the model [?] with data [?] supports that flow develops at the partonic level followed by quark coalescence into hadrons.

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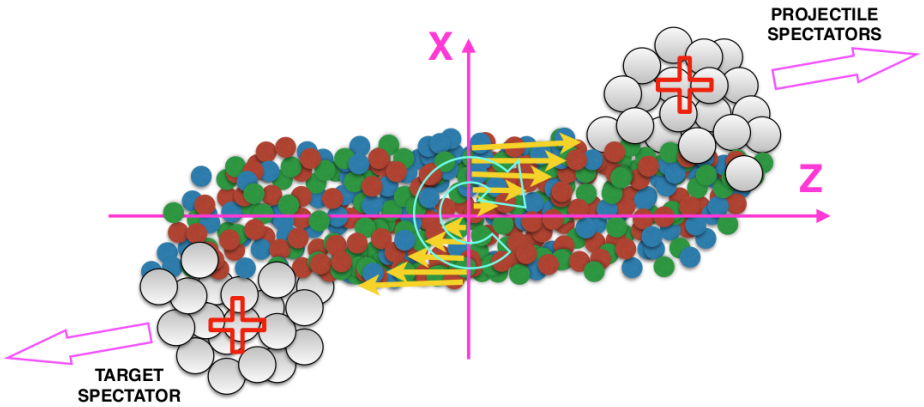

Fig. 1. Schematic view of a nuclear collision with x and z being the impact parameter and beam directions, respectively. The system orbital angular momentum as well as the magnetic field points into the page, opposite to the direction of the y axis. Solid yellow arrows indicate collective velocity field at $z = 0$. Open arrow indicates vorticity of the system [?].

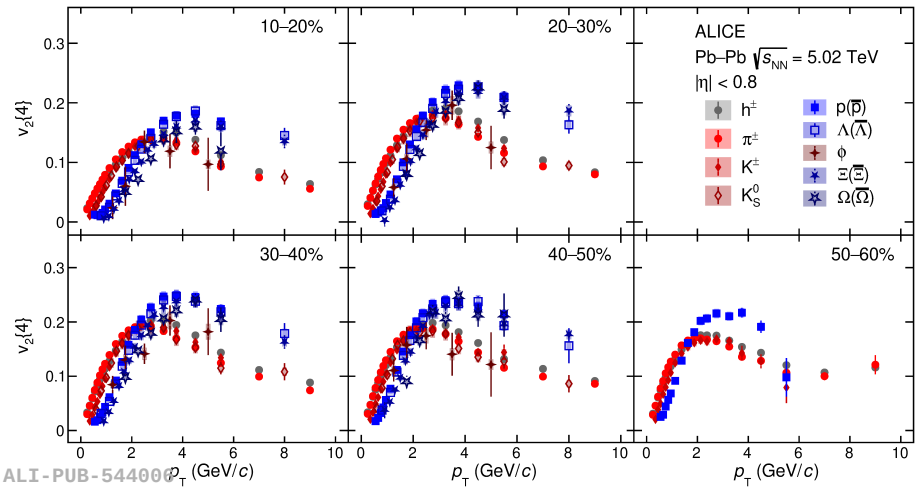

Fig. 2. The transverse momentum differential v_2 for identified hadrons measured with the ALICE detector in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [?]. The data points show the $p_{\rm T}$-dependence of v_2 for different centrality intervals, with vertical error bars representing statistical uncertainties and filled boxes indicating systematic uncertainties.

2. Longitudinal polarization

Evolution of overlapping region in high-energy nuclear collisions is characterized by non-trivial velocity and vorticity fields, resulting in the polarization of the produced particles [?], as depicted in Fig. ??. The vorticity component along the beam axis with a quadrupole structure in the transverse plane due to the spin-orbit coupling from the elliptic flow leads to a longitudinal component of particle spin polarization [?]. These polarization observables allow one to add new dimension in flow measurements.

Because of the parity-violating weak decay of hyperon, the angular distribution of the decay products at the spin 1/2 hyperon rest frame can be expressed as:

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H^* \cdot \mathbf{p}_B^*) \propto 1 + \alpha_H P_H \cos\theta^*$$

where α_H ($\alpha_\Lambda \approx 0.74$) is the hyperon decay parameter, $\mathbf{P}_H^*$ is the hyperon polarization vector, $\mathbf{p}_B^*$ is the unit vector in the direction of the daughter baryon momentum, the Ω is its solid angle. The polarization of Ξ^- is almost fully transferred to daughter Λ [?]. Correspondingly, the second order longitudinal polarization, characterized by the second harmonic sine component in the Fourier decomposition of the polarization along the beam axis (P_z) as a function of the particle azimuthal angle (ϕ) relative to the elliptic flow plane Ψ_2, is evaluated as [?] :

$$P_{z,s2} = \langle P_z \sin(2\phi - 2\Psi_2)\rangle.$$

3. Detection of Λ and Ξ^- hyperon

Λ and Ξ^- hyperons are detected at ALICE Run 3 data taking period in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$= 5.36 TeV via decays $\Lambda \to {\rm p} + \pi^-$ and $\Xi^- \to {\rm p} + \pi^- + \pi^-$. Λ is selected at $0.5 < p_{\rm T} < 10$ GeV/c and rapidity interval $|y| < 0.5$. The invariant mass distributions of Λ and Ξ^- hyperons are presented in Fig. ??. On the bottom plot of left panel of Fig. ?? Λ polarization parameter P_Λ fitted simultaneously with invariant mass is presented. Its value is on the mill level over entire region of $p_{\rm T}$.

4. Longitudinal Λ and Ξ^- polarization

Second order longitudinal Λ polarization is presented as a function of centrality and $p_{\rm T}$ on left and right plots of Fig. ??. $P_{z,s2}$ measurements reveal significant growth with centrality due to increasing anisotropy.

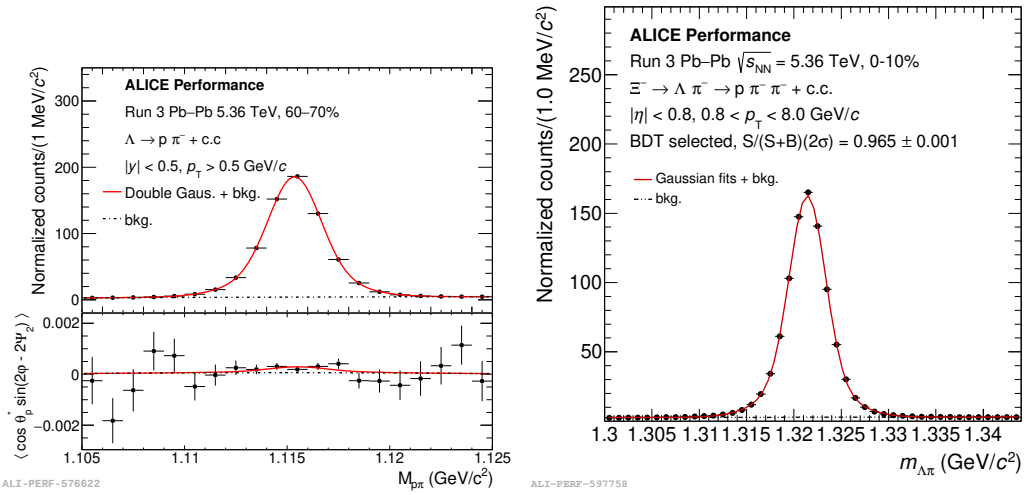

Fig. 3. Left. Λ invariant mass distribution. The black dashed line in the upper (lower) panel - background (background fraction) contribution, the red solid line - total fit function. Bottom plot - polarization vs. mass fitted simultaneously. Right. Ξ^- invariant mass distribution. Fit with the sum of two Gaussians to describe the signal and a second-degree polynomial to describe the background

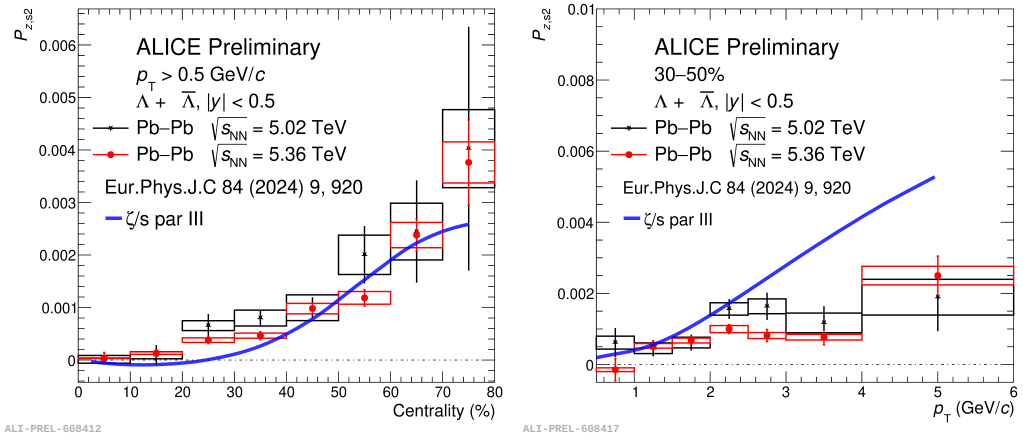

Fig. 4. Left. Dependence of second order longitudinal Λ polarization on centrality. Blue line corresponds to the comparison with model prediction [?]. Right. Dependence of second order longitudinal Λ polarization on p_{T} . Blue line corresponds to the comparison with model prediction [?]. Here and on figures below the vertical error bars and the boxes represent statistical and systematic uncertainties of the data, respectively.

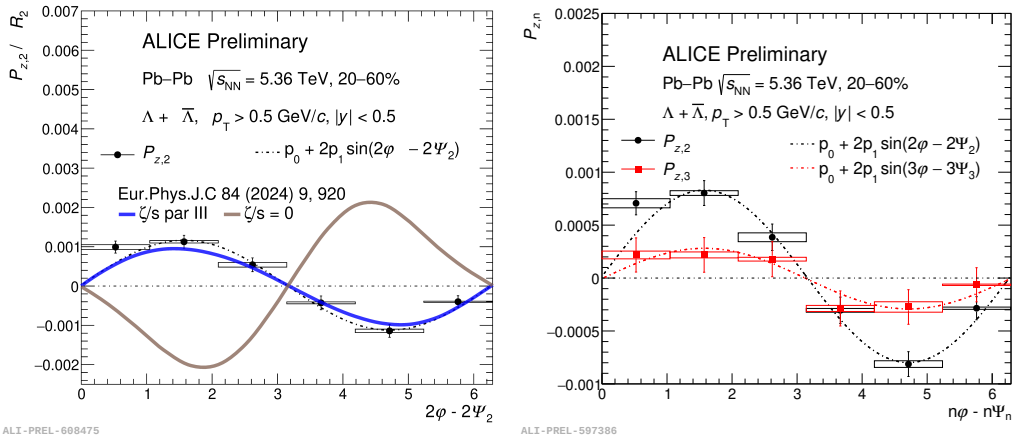

Fig. 5. Left. Second order azimuthal dependence of longitudinal Λ polarization, denoted as $P_{z,2}$. Blue and grey lines correspond to the comparison with model prediction [?] with different parameters ζ/s. Right. Second and third order azimuthal dependence of longitudinal Λ polarization.

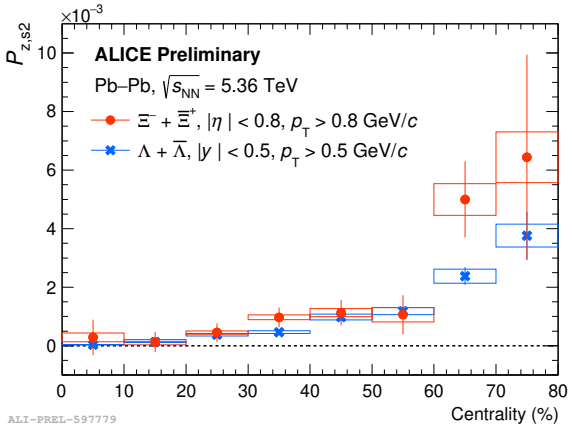

Fig. 6. Dependence of second order longitudinal Ξ^- (red points) and Λ (blue points) polarization on centrality.

On the right plot of Fig. ?? one can see that $P_{z,s2}$ weakly increases with p_T. Centrality dependence is well reproduced by the model assuming a temperature dependent bulk viscosity ζ/s (parametrization III) and an isothermal hadronisation hypersurface including feeddown corrections.

Azimuthal dependent polarization $p_{z,2}$ in Pb-Pb collisions at 5.36 TeV is presented on the left plot of Fig. ?? in comparison with the model [?] calculations. Authors of Ref. [?] noted that 'spin polarization, and in particular its azimuthal angle dependence, can be used as a very effective probe of initial conditions and transport coefficients of the quark–gluon plasma'.

Right plot of Fig. ?? represents first evidence of triangular-flow-induced polarization at LHC energies. Triangular flow $p_{z,s3}$ is compatible with elliptic $p_{z,s2}$ within large uncertainties despite the triangular flow being smaller than elliptic flow.

The first ALICE measurement of longitudinal polarization of Ξ^- in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$= 5.36 TeV is shown in Fig. **??**. Ξ^- is selected at $0.8 < p_{\rm T} < 8$ GeV/c and pseudo-rapidity interval $|\eta| < 0.8$. Boosted decision tree algorithm was applied to have a Ξ^- purity of about 0.96 in all centrality classes. Ξ^- and Λ longitudinal polarization vs collision centrality was measured in Pb-Pb collisions at 5.36 TeV collected in 2023 during the LHC Run 3 data taking. Ξ^- and Λ longitudinal polarization measurements show similar behaviour as a function of centrality as expected for hyperons with the same spin. Future measurements of Ω hyperon with spin 3/2 to test the spin hierarchy are expected.

5. Summary and outlook

The elliptic flow of different barions supports mass ordering at low $p_{\rm T}$ and applicability of quark coalescence models into hadrons [**?**].

The longitudinal polarization of Λ induced by elliptic flow is measured with improved precision using Run 3 data confirming its increasing trend towards more peripheral collisions The longitudinal polarization is well described by the model [**?**].

The first evidence of Λ triangular-flow-induced polarization at LHC energy is presented.

The elliptic flow longitudinal polarization of Ξ^- was measured by ALICE for the first time at the LHC, due to much larger statistics in Run 3.

More precise and differential measurements of the flow and polarization with different sets of particles will be available soon with the full set of Run 3 ALICE data.

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CONFLICT OF INTEREST. The authors of this work declare that they have no conflicts of interest.

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