

# Latest anisotropic flow measurements in Pb–Pb collisions with ALICE: New insights into QGP properties

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**Abstract.** In this proceeding, the latest anisotropic flow measurements at ALICE in Pb–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and 5.36 TeV, are presented. This includes flow coefficients  $v_n$ , mixed harmonic cumulants, and new symmetry plane correlators. These results are compared with state-of-art theoretical calculations, offering unique insights for future model developments and further constraining the properties of QCD matter in heavy-ion collisions.

## 1 Introduction

Understanding the quark–gluon plasma (QGP), a deconfined state of QCD matter created in ultrarelativistic heavy-ion collisions, relies on identifying observables sensitive to distinct collision stages. Anisotropic flow, characterized by Fourier harmonics ( $v_n$ ) of the azimuthal distribution of final state particles, is critical for such study. Measuring collective anisotropic flow and the complex interplay between its Fourier harmonics ( $v_n$ ) and symmetry planes ( $\Psi_n$ ) can effectively disentangle contributions from various collision phases, providing insights into QGP transport properties and the initial state of the system. Recent advances in heavy-ion physics demand higher-precision measurements at extreme energies. This work focuses on ALICE's latest results in Pb–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and 5.36 TeV to probe QGP dynamics. The measurements encompass key observables: flow coefficients  $v_n$ , mixed harmonic cumulants, and pioneering multiharmonic correlations. Differential results, extended to extremely high- $p_T$  regions, are also presented to enrich hard process inputs. The measurements are compared with state-of-art theoretical models to constrain the properties of QGP.

## 2 Analysis Details

The measurements presented in this proceeding are performed with the ALICE detector [1]. The centrality of the collisions is estimated using the multiplicity measured in the forward detector [2]. The charged particles are reconstructed in the central pseudorapidity region based on Inner Tracking System (ITS) and the Time Projection Chamber (TPC). To ensure the reconstruction quality, the position of the primary vertex for each track was required to be within  $\pm 10$  cm from the centre of the detector. The distance of the closest approach to the primary vertex was required to be less than 2 cm in the beam direction. A kinematic selection of the pseudorapidity region  $-0.8 < \eta < 0.8$  is applied for all the tracks. For  $p_T$ -integrated

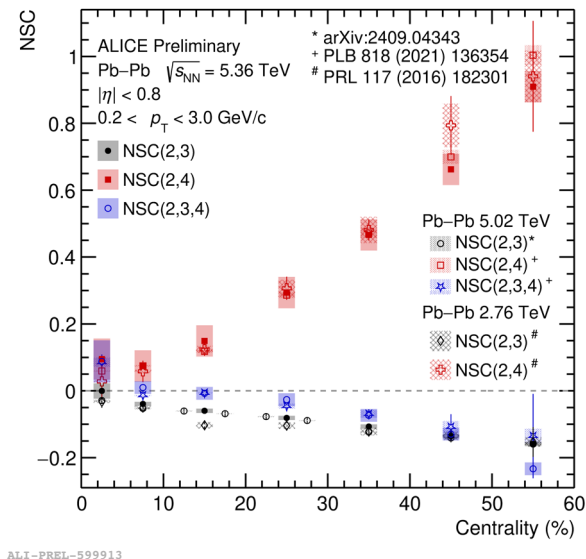
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observables, only tracks within  $0.2 < p_T < 3.0$  GeV/ $c$  are selected. Considering the non-uniform acceptance of the TPC, a correction is applied by utilizing the  $\varphi$  distributions of the reconstructed tracks. To account for the inefficiency of track reconstruction, a  $p_T$ -dependent weight was applied based on GEANT3 simulations [3].

### 3 Results

According to the latest Bayesian analysis [4], normalized symmetric cumulants (NSC) with higher order have greater sensitivities to both initial conditions and transport properties. Among the measured NSCs [4] in Pb–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, NSC(3,2) and NSC(5,4) agree with initial state models (TRENTo initial state [5] and EKRT initial state [6]), suggesting these two correlators are mostly originated from initial state and insensitive to the transport properties, so they can be special probes to the initial conditions.

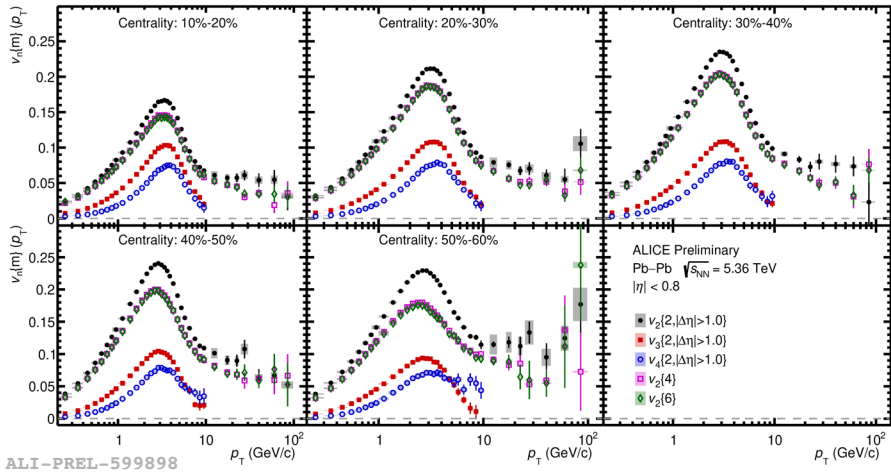


**Figure 1.** Centrality dependence of NSC(2,3), NSC(2,4), NSC(2,3,4).

NSC(m,n) are also updated with the latest measurements at  $\sqrt{s_{NN}} = 5.36$  TeV, presented in Fig. 1. The results are consistent with the measurements at  $\sqrt{s_{NN}} = 2.76$  TeV and 5.02 TeV, showing the weak energy dependences of these correlations. The three measurements conducted in different energies could be merged to have higher precision to provide further constraints on initial conditions and properties of QGP.

In addition to normalized symmetric cumulants, symmetry plane correlations (SPC) are introduced in the latest ALICE measurement [7]. SPCs are found to be sensitive to average bulk viscosity, free streaming time and  $\eta/s$ , therefore the measurements of these correlators provides new constraints on state-of-art hydrodynamic models.

Anisotropic flow coefficient  $v_n$  in dependence on transverse momentum  $p_T$  have different origins according to the  $p_T$  range. For low  $p_T$ , flow coefficient  $v_n$  stems from the initial geometry of overlap and the collectivity behaviour of QGP. While for high  $p_T$ , although  $v_n$  is still affected by the initial geometry, it would be strongly impacted by the path-length



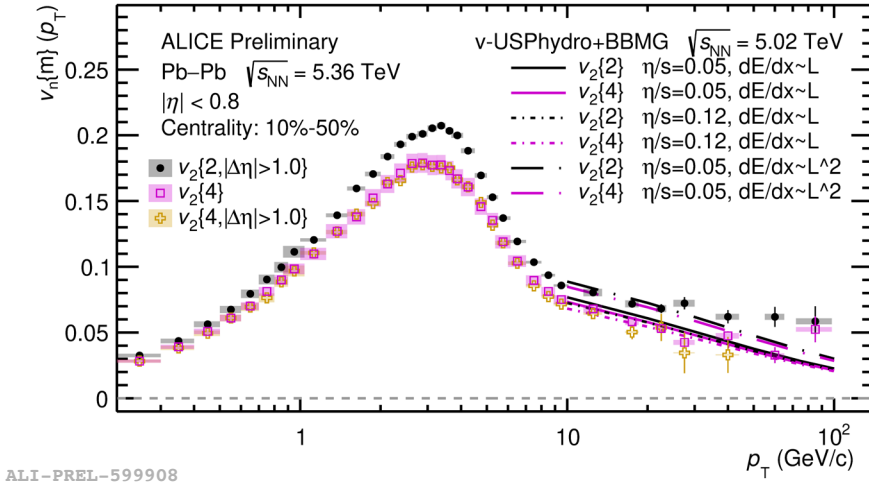
**Figure 2.** Anisotropic flow  $v_n$  with multiparticle cumulants in dependence on  $p_T$  in five centrality regions measured in Pb-Pb collisions.

dependence of parton energy loss. Multiparticle  $v_n$  in dependence on  $p_T$  in five centrality ranges are presented in Fig. 2, including two-particle  $v_n\{2\}$  up to  $n = 4$  and elliptic flow  $v_2$  up to six particles. Multiparticle  $v_2\{2\}$ ,  $v_2\{4\}$ ,  $v_2\{6\}$  are firstly measured up to  $p_T = 100$  GeV/c with the ALICE detector.  $v_3\{2\}$  and  $v_4\{2\}$  are updated with better precisions compared to the measurements at  $\sqrt{s_{NN}} = 5.02$  TeV. The fact that  $v_2\{2\} > v_2\{4\} \approx v_2\{6\}$  suggests that  $v_2$  is strongly affected by initial geometry and its event-by-event fluctuations.

The results in five centrality ranges shown in Fig. 2 are then merged, as the most precise measurements of  $v_n$  in dependence on  $p_T$ , and presented in Fig. 3. With the increased number of events,  $v_2\{4\}$  with  $|\Delta\eta| > 1.0$  is also presented, which is consistent with  $v_2\{4\}$  without  $\eta$  gap suggesting  $v_2\{4\}$  is insensitive to non-flow effect in the presented  $p_T$  range. The measured  $v_n$  in dependence on  $p_T$  are compared to v-USPhydro+BBMG model [8] in Fig. 3, to study the effect of parton energy loss. The differences between the measured  $v_2\{2\}$  and  $v_2\{4\}$  are larger than the ones provided by model. This suggests  $v_2\{2\}$  with  $|\Delta\eta| > 1.0$  still have significant remaining non-flow effects at high  $p_T$ . Among different configurations of the model,  $v_2\{4\}$  prefers the linear path-length dependence of parton energy loss, while its uncertainties cover both the calculations with  $\eta/s = 0.05$  and  $\eta/s = 0.12$ .

## 4 Summary

This proceeding presents ALICE's latest anisotropic flow measurements in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and 5.36 TeV. Key observables include flow coefficients  $v_n$ , mixed harmonic cumulants and new symmetry plane correlators (SPCs). Higher-order normalized symmetric cumulants (NSCs) show sensitivity to initial conditions and transport properties. NSC measurements in Pb-Pb collisions across 2.76, 5.02, and 5.36 TeV exhibit weak energy dependence. SPCs are sensitive to bulk viscosity and other parameters, providing new constraints on hydrodynamic models. Multiparticle  $v_n$  measurements extend to high  $p_T$  (up to 100 GeV/c), with  $v_2\{2\} > v_2\{4\} \approx v_2\{6\}$  indicating strong influence from initial geometry and fluctuations. Comparisons with models reveal larger differences in  $v_2\{2\}$  vs.  $v_2\{4\}$  than predicted, suggesting remaining non-flow effects at high  $p_T$ .



**Figure 3.** Anisotropic flow  $v_n$  with multiparticle cumulants in dependence on  $p_T$  in 10–50% centrality measured in Pb–Pb collisions, compared with v-USPhydro+BBMG model.

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