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Investigating charm-quark dynamics in the QGP via the charm-hadron elliptic flow in Pb–Pb collisions with ALICE

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Abstract. In these proceedings, we report the measurement of the elliptic flow (v_2) of prompt and non-prompt D^0, prompt D^+ and D_s^+ mesons, and, for the first time ever at the LHC, prompt and non-prompt Λ_c^+ baryons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV collected by the ALICE experiment during the LHC Run 3. The analysis is performed at midrapidity ($|y| < 0.8$) in different centrality classes (30–40%, 40–50%, and 60–80% for D^0, D^+, and D_s^+; 30–50% for Λ_c^+). The candidates are reconstructed from hadronic decay channels, and the v_2 is extracted via the scalar-product method. The measurements are compared to light-flavor results and several predictions of models that differently describe heavy-quark transport and hadronization processes in the QGP.

1 Introduction

Heavy quarks (charm and beauty) are excellent probes for investigating the properties of the quark–gluon plasma (QGP) generated in ultra-relativistic heavy-ion collisions. Their participation in the collective motion of the medium can be studied by measuring the elliptic flow of charm hadrons. In non-central heavy-ion collisions, the elliptic flow originates mainly from the initial-state spatial asymmetry [1]. The elliptic flow v_2 is the second-order coefficient of the Fourier decomposition of the particle azimuthal distribution. The harmonic coefficients, which quantify the flow anisotropy (v_n), are calculated as $v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$, where ϕ is the particle's azimuthal angle and Ψ_n denotes the symmetry-plane angle for the n^{th} harmonic [2]. These measurements provide essential inputs to constrain theoretical models describing the charm-quark transport in the QGP, being sensitive to charm thermalization, heavy-quark diffusion coefficients, path-length dependence of parton energy loss, initial-state spatial anisotropy, and hadronization mechanisms. In particular, comparisons between charm meson and baryon v_2 can provide further insights into medium-induced phenomena, such as the interplay of radial flow and the charm-quark hadronization via coalescence. Comparisons between charm and beauty also allow exploration of the mass dependence of relaxation times.

2 Data sample and analysis procedure

In these proceedings, we present measurements of the elliptic flow v_2 of D^0, D^+, and D_s^+ mesons, and, for the first time ever at LHC, Λ_c^+ baryons, in Pb–Pb collisions at $\sqrt{s_{NN}}$ =

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5.36 TeV, within the rapidity interval $|y| < 0.8$. The analysis is based on the data samples collected with the ALICE detector in 2023. After the LHC Long Shutdown 2, the ALICE detector underwent a major upgrade, as detailed in Ref. [3]. The integrated luminosity of this minimum-bias data sample in 2023 reached approximately 1.5 nb^{-1}. The v_2 of prompt D^0, D^+, and D_s^+ mesons is measured in the 30–50%, 30–40%, 40–50%, and 60–80% centrality classes. The v_2 of the prompt and non-prompt Λ_c^+ baryons, as well as the non-prompt D^0 meson, is measured in the 30–50% centrality class. The candidates are reconstructed by combining couples or triplets of tracks that pass some quality cuts, with the correct charge combination. To reduce the combinatorial background and separate the prompt and non-prompt contributions, a multi-class Machine Learning (ML) model, implemented as Boosted Decision Trees (BDT) [4], was trained, following the training strategy described in Ref. [5]. Signal candidates were selected using the BDT-based selections. The inclusive v_2 was extracted using simultaneous fits to the invariant mass spectrum and the v_2 as a function of mass, and the feed-down fraction was estimated using a data-driven method [5]. A linear fit to the inclusive v_2 as a function of the feed-down fraction was used to evaluate the prompt and non-prompt v_2 components.

3 Charm meson v_2

Figure 1 (left) shows the v_2 of prompt D^0, D^+, and D_s^+ mesons in the 30-50% centrality interval, compared to that of inclusive J/ψ in the same centrality interval and of π^+ [6] in 30-40%. This is the first measurement of the prompt D^0 meson v_2 at the transverse momentum p_T < 1 GeV/c. Overall, the v_2 of D^+ mesons shows a good agreement with that of D^0 mesons. At p_T < 4 GeV/c, a mass ordering is observed when comparing v_2 of the heavy-flavor and light-flavor hadrons. The D_s^+ meson v_2 is close to the non-strange D meson v_2, but there is a hint that it is smaller, with a deviation of 2.1 σ. In the interval $4 < p_T < 8$ GeV/c, the prompt D-meson v_2 is compatible with the v_2 of π^+ and both have a decreasing trend. The J/ψ v_2 is smaller than that of D mesons for $p_T < 10$ GeV/c. Above 10 GeV/c, the v_2 measurements of the different particle species are compatible. The common v_2 values of the different particle species for $p_T > 10$ GeV/c can indicate a similar effect from the path-dependent parton energy loss in the QGP. As shown in Fig. 2, the v_2 of prompt D^0, D^+, and D_s^+ mesons in 30-40%, 40-50%,

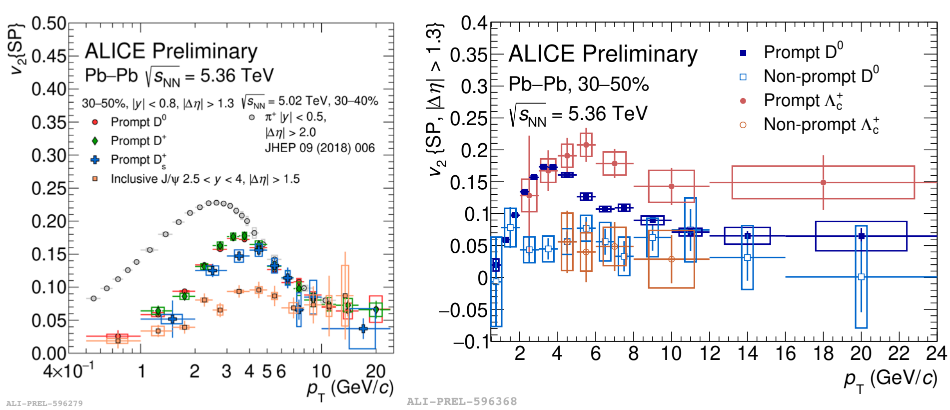

Figure 1. Left: elliptic flow (v_2) of prompt D^0, D^+, and D_s^+ mesons in the 30–50% centrality class is compared to that of inclusive J/ψ and π^+ [6]. Right: measured v_2 of prompt and non-prompt Λ_c^+ baryons and D^0 mesons in the 30-50% centrality interval.

and 60-80% centrality intervals is compared with that of π^+ [6]. A significant modulation of v_2 as a function of p_T is observed in the 30-40% and 40-50% centrality classes, while a flatter p_T trend is observed in 60-80%. This centrality-dependent behavior could provide crucial constraints to the transport properties of QGP, as well as to the interplay of collision eccentricity and QGP size and lifetime in determining the final v_2.

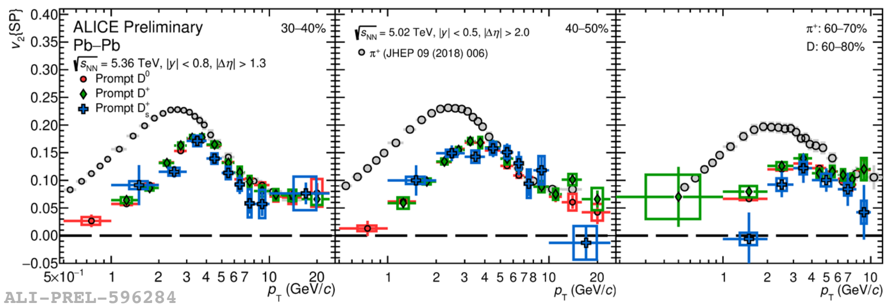

Figure 2. Measured v_2 of prompt D^0, D^+, and D_s^+ mesons, in 30-40% (left), 40-50% (middle), and 60-80% (right), compared to that of π^+.

4 Prompt and non-prompt Λ_c^+-baryon v_2

The Λ_c^+ baryon, composed of one charm quark and two light quarks, is expected to be more sensitive to the coalescence mechanism in QGP. As shown in Fig. 1 (right), for the first time ever at LHC, the v_2 of prompt and non-prompt Λ_c^+ baryons are measured in heavy-ion collisions. At $p_T < 4$ GeV/c, the v_2 of prompt Λ_c^+ baryons is compatible with that of prompt D^0 mesons within uncertainties. At $p_T > 4$ GeV/c, the prompt Λ_c^+-baryon v_2 is larger than that of D^0 mesons with a significance of 3.6 σ, which provides the first evidence of baryon-meson splitting in the charm sector. The non-prompt Λ_c^+-baryon v_2 is consistent with that of non-prompt D^0 mesons within uncertainties, and both are smaller than the prompt v_2. This difference can be ascribed to the larger mass of beauty quarks, which are less influenced by the collective motion and have a longer relaxation time. Figure 3 shows the comparison of the measured v_2 of prompt D^0 mesons and Λ_c^+ baryons with several model predictions [7–12], which incorporate different implementations of heavy-quark transport and hadronization in the QGP. While most models can describe the data reasonably, some show deviations.

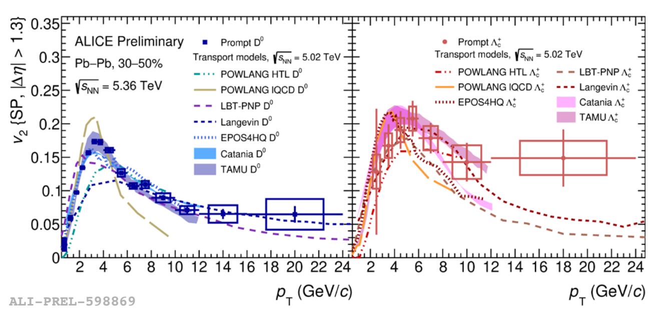

Figure 3. Comparison of measured v_2 of prompt Λ_c^+ baryons and D^0 mesons with model predictions.

5 Summary

In these proceedings, the first measurements of D-meson and Λ_c^+-baryon v_2 performed with ALICE using the 2023 Pb–Pb data collected in Run 3 were reported. In combination with future measurements of R_{AA} in Run 3, the comparison of D-meson and Λ_c^+-baryon v_2 will constrain the description of the hadronization process and its impact on v_2, allowing for a more precise estimate of the heavy-quark diffusion coefficient. Overall, with the inclusion of 2024 and 2025 data, we expect to analyze a data sample with a factor of 3 larger than the current one.

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