Investigation of early magnetic field and angular momentum in ultrarelativistic heavy-ion collisions via D^{*+} spin alignment with ALICE

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Abstract. Heavy quarks, i.e. charm and beauty, are produced at the initial stages of heavy-ion collisions, on a time scale shorter than the medium formation time, and are sensitive to the initial angular momentum of the system and the magnetic field produced perpendicular to the reaction plane (defined by the impact parameter direction and beam direction) in non-central heavy-ion collisions. In the presence of a large angular momentum and initial magnetic field, the charm quark can be polarized. Experimentally, the heavy-flavor polarization can be probed by measuring the spin density matrix element (ρ_{00}) of spin-1 mesons such as D^{*+} mesons. Any deviation of the parameter from 1/3 can be attributed to the spin alignment of the D^{*+} meson.
In these proceedings, we present the first measurement of the ρ_{00} parameter of prompt D^{*+} mesons in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$= 5.02 TeV, exploiting the data sample collected by the ALICE Collaboration during LHC Run 2. A comparison with the J/ψ polarization measurement is also reported to investigate the effect of the magnetic field. Moreover, the ρ_{00} parameter of D^{*+} mesons measured in pp collisions is also presented.

1 Introduction

In ultrarelativistic nuclear collisions, the produced system evolves through various phases. In non-central collisions, charged spectator motion produces a magnetic field ($B \approx 10^{15}$ T) in very early stages of the collisions, which decreases with time [1]. Additionally, a highly vortical system with orbital angular velocity ($\omega \approx 10^{22}$ s^{-1}) is produced due to the spectator motion [2] which results in a large orbital angular momentum (L). The two effects can preferentially align particle's spin projection along the spin quantization axis through spin-orbit coupling. Charm quarks and antiquarks are produced in the early stages (~ 0.1 fm/c) of the collision. Therefore, they are more sensitive to the high intensity of the electromagnetic fields compared to light quarks [3]. In presence of the large L and strong B fields, the charm quarks and antiquarks become polarized. Eventually, this polarization is reflected in the spin alignment of vector mesons (J/ψ, D^{*+}) formed by these quarks [3].

Vector meson spin alignment is quantified by measuring the spin density matrix element (ρ_{00}) which is extracted by parameterizing the angular distribution of D^{*+} decay products using the following expression:

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$$\frac{dN}{d\cos\theta^*} = N_0\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right], \quad (1)$$

Here, θ^* is the angle between the momentum of the daughter pion and the polarization axis in the D^{*+} rest frame, and N_0 is the normalization constant. In Pb–Pb collisions, ρ_{00} is measured in the direction of L and B fields, i.e. the direction orthogonal to the reaction plane. In pp collisions, it is measured in the helicity frame, which is defined as the direction of a vector meson in the laboratory frame. The spin alignment of vector meson is influenced by two hadronization mechanisms, which dominate charm-meson formation at different p_T. At low p_T, spin alignment depends on the magnitude of polarization of the both recombining quark and antiquark. At high p_T, it depends on the magnitude of polarization of the fragmenting quark (or antiquark) and its correlation with the constituent antiquark (or quark) [4, 5].

The ALICE apparatus [7] allows for the reconstruction of D^{*+} mesons at midrapidity ($|y| < 0.8$) through the decay channel $D^{*+} \rightarrow D^0\,(K^-\pi^+)\,\pi^+$ and respective charge conjugates. The D^{*+} mesons formed in charm-quark hadronization, or in decays of excited charm states, are defined as prompt, while those produced in beauty hadron decays are called non-prompt D^{*+}. The inclusive charmonium states are reconstructed down to $p_T = 0$ at forward rapidity ($2.5 < y < 4$) through the dimuon decay channel. The Time Projection Chamber (TPC) and Inner Tracking System (ITS) detectors are used for precise tracking of the pions and kaons from the D^{*+} decay at midrapidity. The TPC offers outstanding particle identification capabilities down to very low p_T (around 200 MeV/c) via the measurement of specific energy loss in a gaseous medium.

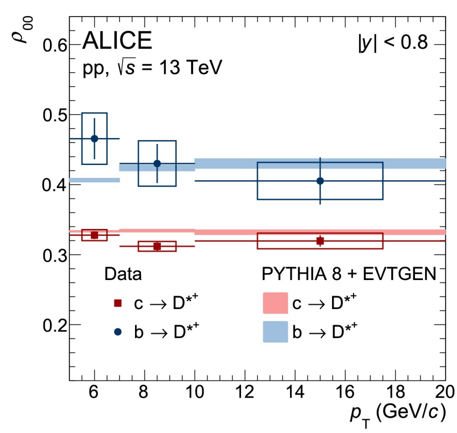

Figure 1. ρ_{00} of prompt and non-prompt D^{*+} as a function of p_T measured in the helicity frame in pp collisions at $\sqrt{s}$ = 13 TeV [6].

The ITS consists of six layers of silicon detectors. The two innermost layers, equipped with pixel detectors, provide the spatial resolution needed to distinguish between prompt and non-prompt D^{*+} mesons at midrapidity in Pb–Pb collisions. Boosted Decision Trees are used to reduce the combinatorial background and separate the prompt and non-prompt components. The muon spectrometer is employed to trigger on and reconstruct muon tracks at forward pseudorapidity.

2 Results

Figure 1 shows the first measurement of the prompt and non-prompt D^{*+} spin alignment at the LHC. The prompt and non-prompt ρ_{00} are shown as a function of p_T in the helicity frame at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV. The measured ρ_{00} for prompt D^{*+} is consistent with 1/3. Thus, there is no evidence of spin alignment of prompt D^{*+} with respect to the helicity axis. In contrast, a significant spin alignment is observed for non-prompt D^{*+}, as expected from the helicity conservation in weak decays of beauty hadrons. The model predictions, obtained from PYTHIA 8 + EvtGen [8, 9], are consistent with these measurements. These results serve as a benchmark for D^{*+} spin alignment measurements in Pb–Pb collisions.

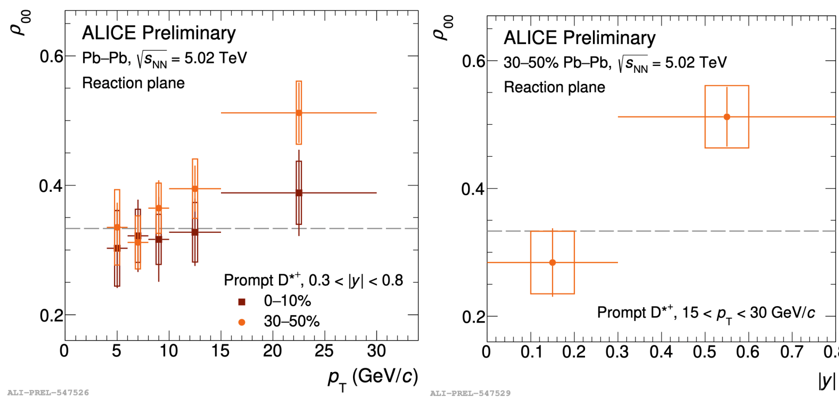

Figure 2. (Left) ρ_{00} of prompt D^{*+} as a function of p_T measured with respect to reaction plane in the 0–10% and 30–50% centrality ranges, and (Right) as a function of rapidity in $15 < p_T < 30$ GeV/c in the 30–50% centrality range in Pb–Pb collisions.

Figure 2 demonstrates the first measurement of D^{*+} spin alignment with respect to the reaction plane in the 0–10% and 30–50% centrality intervals in Pb–Pb collisions. The left panel of Fig. 2 shows prompt D^{*+} ρ_{00} as a function of p_T in the $0.3 < |y| < 0.8$ rapidity region. The data show a hint of rising trend with p_T in 30–50% centrality interval. In the 0–10% centrality interval, ρ_{00} is consistent with 1/3. In the 30–50% centrality interval, it is larger than 1/3 at high p_T, where hadronization is expected to occur mainly through quark fragmentation. This case is further investigated as a function of rapidity. In the right panel of Figure 2, ρ_{00} of prompt D^{*+} is shown in two different rapidity ranges: at midrapidity ($|y| < 0.3$) and at slightly more forward rapidity ($0.3 < |y| < 0.8$), measured at $15 < p_T < 30$ GeV/c in 30–50% centrality. At midrapidity, ρ_{00} does not show any significant deviation from 1/3, while at forward rapidity it is significantly larger than this value. At large rapidity, the electromagnetic fields decrease slowly in time and charm quarks with large momentum might be more influenced by those fields [3]. Theoretical predictions are necessary to make conclusive remarks on these findings.

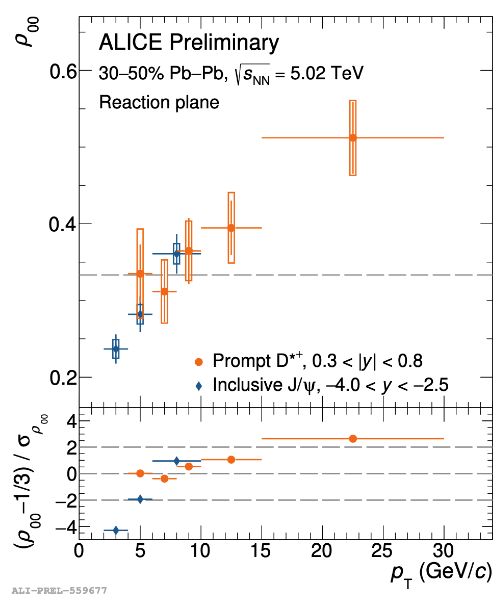

Figure 3. ρ_{00} of prompt D^{*+} and inclusive J/ψ as a function of p_T measured with respect to the reaction plane in 30–50% centrality range at forward rapidity in Pb–Pb collisions.

Depending on the hadronization mechanism, quark polarization is reflected in the hadrons. Both J/ψ and D^{*+} possess a charm quark (or an antiquark), therefore, polarization of these hadrons might be governed by similar processes. Figure 3 shows a comparison of the prompt D^{*+} ρ_{00} with that of inclusive J/ψ as a function of p_T measured with respect to reaction plane at forward rapidity in 30–50% centrality interval in Pb–Pb collisions. Similar to prompt D^{*+}, the ρ_{00} of inclusive J/ψ rises with p_T. The ρ_{00} for prompt D^{*+} and inclusive J/ψ are compatible within uncertainties in the overlapping p_T range. The inclusive J/ψ ρ_{00} is significantly smaller (by 4σ) than 1/3 at p_T smaller than 5 GeV/c, where J/ψ is dominantly produced by charm and anti-charm recombination.

3 Summary

The first results of prompt D^{*+} spin alignment with respect to the reaction plane in Pb–Pb collisions were presented. A significant spin alignment is observed for prompt D^{*+} at high p_T in 30–50% centrality interval at rapidity $0.3 < |y| < 0.8$ in Pb–Pb collisions. This observation supports the hypothesis that electromagnetic fields can polarize the charm quarks at the large momentum produced during the early stages of collisions. The prompt D^{*+} results are consistent with inclusive J/ψ polarization in the overlapping p_T region measured with respect to the reaction plane. A comparison with theoretical predictions is necessary to obtain a robust interpretation of the data.

Since 2022, ALICE has been collecting data in a continuous readout mode in pp and Pb–Pb collisions. Eventually, the total size of this data sample from minimum-bias pp and Pb–Pb collisions will be significantly larger than that collected in LHC Run 2 and will allow more differential spin alignment measurements at high p_T, up to 100 GeV/c.

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