

First measurement of D^{*+} vector meson spin alignment in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV



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ABSTRACT: The first measurement of prompt D^{*+} -meson spin alignment in ultrarelativistic heavy-ion collisions with respect to the direction orthogonal to the reaction plane is presented. The spin alignment is quantified by measuring the element ρ_{00} of the diagonal spin-density matrix for prompt D^{*+} mesons with $4 < p_{\text{T}} < 30$ GeV/ c in two rapidity intervals, $|y| < 0.3$ and $0.3 < |y| < 0.8$, in central (0–10%) and midcentral (30–50%) Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Evidence of spin alignment $\rho_{00} > 1/3$ has been found for $p_{\text{T}} > 15$ GeV/ c and $0.3 < |y| < 0.8$ with a significance of 3.1σ . The measured spin alignment of prompt D^{*+} mesons is compared with the one of inclusive J/ψ mesons measured at forward rapidity ($2.5 < y < 4$).

KEYWORDS: Heavy Ion Experiments, Particle Correlations and Fluctuations, QCD, Quark Gluon Plasma

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1 Introduction

High-energy heavy-ion collision experiments study the strongly interacting quantum chromodynamics (QCD) matter at very high temperature and extreme energy densities, where a phase of deconfined quarks and gluons called quark–gluon plasma (QGP) is expected to be formed [1]. Theoretical studies, alongside experimental evidences, have shown that the QGP behaves as a strongly interacting fluid. Several properties of the QGP medium, such as shear viscosity to entropy-density ratio, stopping power, and diffusion coefficients, have been measured, leading to the discovery of an emergent property of QCD matter that characterises it as a nearly perfect fluid [1]. Recently there has been a thoughtful understanding of the QGP properties in systems possessing large angular momentum and/or immersed in a strong magnetic field. In non-central heavy-ion collisions with a non-zero impact parameter, defined as the distance between the centers of the two colliding nuclei, a large angular momentum of $O(10^7 \hbar)$ [2] and a strong magnetic field of $O(10^{15} \text{ T})$ [3] are expected to be created at LHC energies in the direction perpendicular to the reaction plane, defined by the direction of the impact parameter of the two nuclei and the beam direction. During the collision, a sizable fraction of the total angular momentum is transferred to the created QGP fluid and the remaining fraction is carried away by the spectator nucleons that do not participate in the collision. The angular momentum can be transferred to the QGP in the form of fluid vorticity along the direction of the angular momentum. In general, the relation between angular momentum and fluid vorticity is not straightforward and depends on the local fluid density that affects the moment of inertia through a complex dependence in case of an expanding system. The theory calculation reported in ref. [4] suggests that while the deposited angular momentum in the QGP medium is conserved in time, the fluid vorticity strongly depends on the time evolution of the fluid, in particular the fluid vorticity is significantly higher in the initial stage of the QGP evolution. As opposed to the angular momentum, the magnetic field is short lived (a fraction of fm/c) and its lifetime depends on the conductivity of the

medium [5]. In the presence of fluid vorticity and an intense magnetic field, quarks in the QGP would be polarised and their polarisation can be further transferred to the final state hadrons during the process of hadronisation.

The polarisation of a vector meson is challenging to measure in strong hadronic decays [6]. However information about it can be inferred via the measurement of the spin alignment, which is defined by the deviation of the spin density matrix element [6] ρ_{00} from $1/3$. The value of ρ_{00} implies the probability of finding a vector meson in the state with spin projection zero out of possible states with spin projection $-1, 0, \text{ and } 1$ [7]. If the spin of the particles is oriented isotropically, then $\rho_{00} = 1/3$. The spin alignment is studied by measuring the angular distribution of the decay products of vector mesons in the rest frame of the decaying vector meson and a quantisation/polarisation axis which in heavy-ion collisions can be defined as the perpendicular to the reaction plane. The angular distribution of the vector meson decays to two spin zero hadrons is expressed as

$$\frac{dN}{d \cos \vartheta^*} \propto [1 - \rho_{00} + (3\rho_{00} - 1) \cos^2 \vartheta^*], \quad (1.1)$$

where ϑ^* is the angle between the momentum of one of the decay daughters in the rest frame of the vector meson with respect to the quantisation axis [8]. While in proton–proton (pp) collisions the helicity axis, i.e. the direction of the decaying hadron in the laboratory frame, is used as the quantisation axis, in heavy-ion collisions the direction defined by the angular momentum and the magnetic field vectors is used. The directions of these two quantisation axes are correlated through the anisotropic collective expansion observed in heavy-ion collisions, which is quantified by coefficients in a Fourier decomposition of the azimuthal-angle distribution of final-state particle momenta, with the second-harmonic coefficient v_2 , called elliptic flow [9]. First evidence of light-flavour vector meson (K^{*0} and ϕ) spin alignment in heavy-ion collisions was reported by the ALICE Collaboration [10] and in later years ϕ meson spin alignment was also observed by the STAR Collaboration [11]. At LHC energies, a negative deviation ($< 1/3$) of the parameter ρ_{00} for K^{*0} and ϕ mesons was measured, whereas at RHIC energies a positive deviation ($> 1/3$) of ρ_{00} for ϕ mesons was observed. The measured spin alignment of light-flavour vector mesons at RHIC and LHC energies are surprisingly much larger compared to expectations from the measurement of global Λ polarisation in the non-relativistic thermodynamic limit considering the vorticity as the only source of polarisation [10, 12]. This triggered new theory developments to understand the origin of vector meson spin alignment. Although the hyperon polarisation is sensitive to the average quark polarisation, the spin alignment of vector mesons is sensitive to the local fluctuation or correlation of quark–antiquark spin [13]. On one hand, theoretical studies based on local polarisation originating from the anisotropic expansion of the fireball [14, 15], fluctuations of quark polarisation in turbulent colour fields due to locally fluctuating axial charge currents [16], and local spin correlation induced by the colour fields in the glasma phase [17] showed that these mechanisms could lead to large vector meson spin alignment. In refs. [6, 18] hadronisation via coalescence (recombination of polarised quarks) is predicted to give $\rho_{00} < 1/3$, however its deviation from $1/3$ is expected to be very small compared to the reported measurements. On the other hand, the observed $\rho_{00} > 1/3$ for ϕ mesons at RHIC energies can be qualitatively explained by models that incorporate the fluctuation of a ϕ

meson field [19–21]. In this model, the strange and antistrange quarks can be polarised by the ϕ meson field induced by the current of pseudoscalar bosons when they form the ϕ meson. The local correlation or fluctuation of the vector-meson field leads to $\rho_{00} > 1/3$ for ϕ mesons produced from the coalescence of polarised strange and antistrange quarks. Furthermore, recent calculations based on the holographic approach also predict a significant spin alignment of flavourless vector mesons due to the modification of the spectral function for different spin channels in the presence of thermal background [22]. Calculations based on the holographic approach are also qualitatively consistent with the ϕ meson spin alignment measurements at RHIC energies. Despite the several theoretical approaches, a single consistent picture to describe the light flavour vector meson spin alignment across different collision energies and particles does not exist yet and requires further theoretical developments.

Unlike light-flavour hadrons, which originate at a late stage of a heavy-ion collision, the heavy-flavour hadrons could be more sensitive to the initial stages as the charm quarks are predominantly produced in the initial hard scattering processes with typical production time of $O(0.1 \text{ fm}/c)$, which is lower than the QGP formation time $O(1 \text{ fm}/c)$ [1]. Therefore, charm quarks are expected to be affected more by the magnetic field and vorticity, which are significantly larger at the time of charm-quark formation [23]. Additionally, high transverse-momentum (p_T) charm quarks are likely to retain a greater degree of this polarisation due to their shorter interaction time with the medium constituents, also depending on their spin-relaxation time [24]. The ALICE Collaboration has recently measured a significant spin alignment of inclusive J/ψ vector mesons [25] at low p_T and at forward rapidity which is qualitatively consistent with the expectation from the calculation based on the holographic approach reported in ref. [22]. The ρ_{00} parameter of D^{*+} mesons has been measured in pp collisions by the ALICE Collaboration for both prompt (directly originating from charm-quark hadronisation, or the decay of excited charm hadron decays) and non-prompt (from beauty-hadron decays) production [26]. In the case of prompt production, no significant spin alignment was observed, while in the case of non-prompt D^{*+} mesons a $\rho_{00} > 1/3$ was found, as a consequence of the helicity conservation in weak decays [26].

In this paper, we report the first measurement of prompt open charm hadron (D^{*+}) spin alignment at midrapidity ($|y| < 0.8$) in heavy-ion collisions. The measurement of the ρ_{00} of prompt D^{*+} mesons in Pb–Pb collisions represents useful input for the modeling of charm-hadron spin alignment in heavy-ion collisions and can shed light on the propagation of charm quarks under extreme magnetic fields and vorticity expected at the initial stages of heavy-ion collisions. In addition, measurements at high p_T are important to understand how the quark polarisation is propagated to final-state hadrons when the underlying hadronisation process is quark fragmentation. The organisation of the article is as follows. The experimental apparatus, data analysis technique, sources of systematic uncertainties are described in sections 2, 3, 4, respectively. Results are shown in section 5, and the article is finally summarised in section 6.

2 Experimental apparatus

The ALICE apparatus comprises a central barrel, which is composed of a set of detectors for charged-particle reconstruction and identification at midrapidity, a forward muon spectrometer, and various forward and backward detectors for triggering and event characterisation. A

detailed description of the detectors and an overview of their typical performances can be found in refs. [27, 28]. The main detectors used for the analysis presented in this paper are the Inner Tracking System (ITS), a six-layer silicon detector used to track charged particles and for the reconstruction of primary and secondary vertices; the Time Projection Chamber (TPC), which provides track reconstruction as well as particle identification via the measurement of the specific ionisation energy loss dE/dx ; and the Time-Of-Flight (TOF) detector, an array of Multigap Resistive Plate Chambers that provides particle identification via the measurement of the flight time of the particles. These detectors cover the pseudorapidity interval $|\eta| < 0.9$ and are located in a large solenoidal magnet providing a uniform magnetic field of 0.5 T parallel to the LHC beam direction. In addition, the V0 detector, which consists of two arrays of 32 scintillators each, covering the full azimuth in the pseudorapidity intervals $-3.7 < \eta < -1.7$ (V0C) and $2.8 < \eta < 5.1$ (V0A), and the Zero Degree Calorimeters (ZDC), located at 112.5 m from the interaction point on either side, were used for event selection and classification.

The analysis was performed using samples of Pb–Pb collisions recorded in 2018 during the second LHC data-taking period with a minimum bias trigger which required coincident signals in the V0A and V0C detectors. Two additional trigger classes were used to enrich the sample of central and midcentral collisions via an online event selection based on the V0-signal amplitude. In order to have a uniform acceptance in pseudorapidity, only events with a primary vertex reconstructed within ± 10 cm from the centre of the detector along the beam-line direction were considered in the analysis. Collisions were classified into centrality intervals, defined in terms of percentiles of the hadronic Pb–Pb cross section, based on the V0 signal amplitude, as described in detail in ref. [29]. Background events due to the interaction of one of the beams with residual gas in the vacuum tube and other machine-induced backgrounds were rejected offline using the V0 and the ZDC timing information [28]. The samples of central and midcentral collisions consist of approximately 100×10^6 and 85×10^6 events in the 0–10% and 30–50% centrality intervals, corresponding to integrated luminosities of $\mathcal{L}_{\text{int}} \simeq 130 \mu\text{b}^{-1}$ and $\mathcal{L}_{\text{int}} \simeq 56 \mu\text{b}^{-1}$, respectively.

3 Data analysis

The V0 detectors were used to determine the second-order harmonic event plane ψ_2 , which is chosen as an estimator for the reaction plane of the collision. The ψ_2 angle is defined as

$$\psi_2 = \frac{1}{2} \tan^{-1} \left(\frac{Q_{2,y}}{Q_{2,x}} \right), \tag{3.1}$$

where $Q_{2,x}$ and $Q_{2,y}$ are the second-harmonic flow-vector components computed as

$$Q_{2,x}^{\text{V0}} = \sum_{k=1}^{N_{\text{cells}}} w_k \cos(2\varphi_k), \quad Q_{2,y}^{\text{V0}} = \sum_{i=k}^{N_{\text{cells}}} w_k \sin(2\varphi_k). \tag{3.2}$$

In the above formula, N_{cells} corresponds to the 64 cells of the full V0 detector, φ_k is the azimuthal angle of the centre of the cell k and w_k is the amplitude of the signal in cell k , once the gain of the single channels is equalised in each ring and the recentering is applied to

correct effects of non-uniform acceptance [30]. The event-plane resolution R_2 , defined as

$$R_2 = \sqrt{\frac{\langle \cos [2(\psi_2^{V0} - \psi_2^{\text{TPC } \eta > 0})] \rangle \langle \cos [2(\psi_2^{V0} - \psi_2^{\text{TPC } \eta < 0})] \rangle}{\langle \cos [2(\psi_2^{\text{TPC } \eta > 0} - \psi_2^{\text{TPC } \eta < 0})] \rangle}}, \quad (3.3)$$

was determined by correlating three sub-events of charged particles reconstructed in the V0 itself, in the positive ($0 < \eta < 0.8$) and negative ($-0.8 < \eta < 0$) semivolumes of the TPC. In the formula in eq. (3.3), ψ_2^{V0} is the second-order harmonic event plane angle determined with the V0 detector, while $\psi_2^{\text{TPC } \eta > 0}$ and $\psi_2^{\text{TPC } \eta < 0}$ are those computed using charged-particle tracks reconstructed in the TPC. The brackets $\langle \rangle$ denote the average over all the events within a centrality class. The event-plane resolution obtained with the above formula was about $R_2 = 0.62$ for the 0–10% centrality class and $R_2 = 0.77$ for the 30–50% centrality class.

The D^{*+} mesons and their charge conjugates were measured at midrapidity ($|y| < 0.8$) via the $D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+) \pi^+$ decay channel, with branching ratio $\text{BR} = (2.67 \pm 0.03)\%$ [31]. The D^0 -decay candidates were defined combining pairs of tracks reconstructed with the ITS and TPC detectors having the expected charge combinations. Each track was required to have $|\eta| < 0.8$, $p_T > 0.3 \text{ GeV}/c$, at least 70 (out of 159) associated space points in the TPC, and a minimum of two hits in the ITS, with at least one in either of the two innermost layers to ensure a good pointing resolution. An additional low- p_T track having $|\eta| < 0.8$, $p_T > 50 \text{ MeV}/c$, and at least two hits in the ITS was then added to form D^{*+} -meson candidates. The analysis was based on the reconstruction of decay-vertex topologies of D^0 mesons displaced from the interaction vertex. In particular, the proper decay length of D^0 mesons of $c\tau \approx 123 \text{ } \mu\text{m}$ and that of beauty hadrons of $c\tau \approx 500 \text{ } \mu\text{m}$ were exploited to resolve the D^0 -meson decay vertices. In order to reduce the large combinatorial background and to separate the contribution of D^{*+} mesons originating from charm hadronisation or excited charm-hadron decays (prompt) from those stemming from beauty-hadron decays (non-prompt), a multiclass classification algorithm based on Boosted Decision Trees (BDTs) was used [32, 33]. The variables used to train the BDT algorithm to distinguish among prompt, non-prompt D^{*+} mesons and background candidates were based on i) the distance between the reconstructed D^0 -meson decay vertex and the primary vertex, ii) the D^0 -meson distance of closest approach to the interaction vertex, iii) the cosine of the pointing angle between the D^0 -meson candidate line of flight and its reconstructed momentum vector, and iv) the particle identification (PID) information of the decay tracks. The PID information was provided by the specific energy loss and the flight time of particles measured with the TPC and TOF detectors, respectively. Given the three classes of candidates, the BDT output scores are related to the probability of each candidate to be a prompt D^{*+} meson, a non-prompt D^{*+} meson, or combinatorial background.

Signal samples of prompt and non-prompt D^{*+} mesons for the BDT training were obtained from Monte Carlo simulations based on the HIJING 1.36 [34] event generator. In each simulated event, additional $c\bar{c}$ - and $b\bar{b}$ -quark pairs were injected using the PYTHIA 8.243 event generator [35] (Monash-13 tune [36]) and D^{*+} mesons were forced to decay into the hadronic channel of interest for the analysis. The generated particles were propagated through the detector using the GEANT 3 transport package [37]. The conditions of all the ALICE detectors in terms of active channels, gain, noise level, and alignment, and their evolution

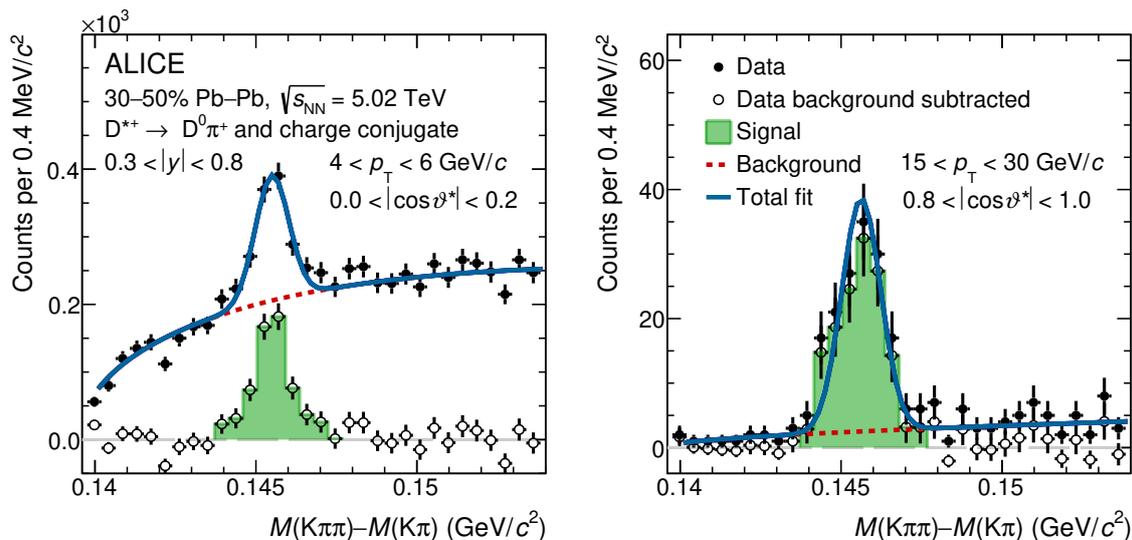


Figure 1. Invariant-mass distributions ΔM of D^{*+} candidates with $4 < p_T < 6$ GeV/ c and $0.0 < |\cos \vartheta^*| < 0.2$ (left panel), and with $15 < p_T < 30$ GeV/ c and $0.8 < |\cos \vartheta^*| < 1.0$ (right panel) in the rapidity interval $0.3 < |y| < 0.8$ for the 30–50% centrality class.

with time during the data taking period, were taken into account in the simulations. The background samples were obtained from data in the sideband region of the invariant-mass distribution $\Delta M = M(K\pi\pi) - M(K\pi)$. The sideband region was chosen as the invariant-mass interval $150 < \Delta M < 170$ MeV/ c^2 , where no D^{*+} signal is present. Independent BDT models were trained for the different p_T intervals and centrality classes of the analysis.

The analysis was performed in five p_T intervals within the $4 < p_T < 30$ GeV/ c range, and in the 0–10% and 30–50% centrality classes. Furthermore, the D^{*+} candidates were divided into two rapidity intervals, $|y| < 0.3$ and $0.3 < |y| < 0.8$. A selection on the BDT score related to the probability to be background was applied in order to suppress the large combinatorial background, while a selection on the BDT score related to the probability to be a prompt D^{*+} meson was required to reduce the contamination from non-prompt D^{*+} mesons. For each centrality, p_T , and rapidity range, the raw yield of D^{*+} mesons was extracted with a fit to the distribution of the invariant mass ΔM in five $|\cos \vartheta^*|$ intervals, ϑ^* being the angle between the momentum of either the D^0 -meson or the pion daughters in the rest frame of the D^{*+} meson with respect to the quantisation axis, defined as the direction orthogonal to the plane determined by the \mathbf{Q}_2 flow vector and the beam axis. The ΔM distribution was fitted with a combination of the Gaussian function corresponding to the D^{*+} signal and a background function. The shape of the background distribution was described with the function $p_0 \sqrt{\Delta M - M_\pi} e^{p_1(\Delta M - M_\pi)}$, where p_0 and p_1 are free parameters and M_π is the charged-pion rest mass. The signal was evaluated with a bin counting method, i.e. as the integral of the counts in the invariant-mass distribution within $\pm 3\sigma$, where σ is the Gaussian width, after subtracting the fitted background function. Figure 1 shows two examples of fits to the ΔM distributions of D^{*+} candidates with $4 < p_T < 6$ GeV/ c and $0.0 < |\cos \vartheta^*| < 0.2$ (left panel), and with $15 < p_T < 30$ GeV/ c and $0.8 < |\cos \vartheta^*| < 1.0$ (right panel) in the rapidity interval $0.3 < |y| < 0.8$ for the 30–50% centrality class. The width

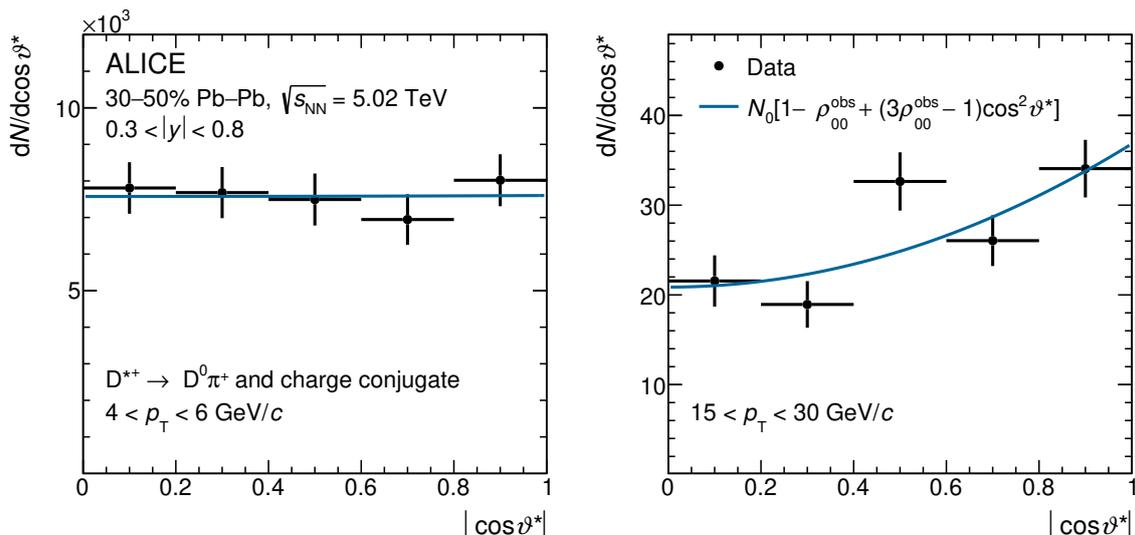


Figure 2. Acceptance and efficiency corrected angular distributions of the decaying pion in the rest frame of the D^{*+} candidates with $4 < p_T < 6$ GeV/c and with $15 < p_T < 30$ GeV/c in the rapidity interval $0.3 < |y| < 0.8$ for Pb–Pb collisions in the 30–50% centrality class. The distributions are fitted with the function from eq. (1.1). Only statistical uncertainties are shown.

of the Gaussian function for the D^{*+} signal was fixed to the value from the MC simulation to improve the stability of the fits.

The raw yields were corrected for the product of the geometrical acceptance and the reconstruction and selection (including BDT) efficiency factors ($\text{Acc} \times \epsilon$) for D^{*+} mesons in each $\cos\vartheta^*$ and p_T intervals. The MC simulations used to compute these correction factors are analogous of those adopted for the BDT trainings. The impact on the ρ_{00} measurement due to the shape of the $\cos\vartheta^*$ and p_T distributions in the MC simulations was studied by weighting the generated MC distributions in order to reproduce the measured $\cos\vartheta^*$ and p_T distributions. The variation of the estimated ($\text{Acc} \times \epsilon$) values was found to be smaller than 0.1% in the analysed p_T intervals. The corrected angular distributions of D^{*+} mesons with $4 < p_T < 6$ GeV/c and $15 < p_T < 30$ GeV/c in the $0.3 < |y| < 0.8$ rapidity interval for the 30–50% Pb–Pb collisions are shown in the left and right panels of figure 2, respectively. The absolute value of $\cos\vartheta^*$ was used considering the symmetry with respect to zero expected for the angular distribution (see eq. (1.1)) and the limited size of the analysed data sample. The angular distributions were fitted with the functional form given in eq. (1.1) to extract the ρ_{00}^{obs} values for each p_T , rapidity, and centrality interval.

In order to obtain the ρ_{00} parameter with respect to the direction orthogonal to the reaction plane, a correction due to the finite resolution of the second-harmonic event plane R_2 has to be applied [10, 38]. In particular, the corrected ρ_{00} parameter can be computed as

$$\rho_{00} = \frac{1}{3} + \left(\rho_{00}^{obs} - \frac{1}{3} \right) \cdot \frac{4}{1 + 3R_2}, \quad (3.4)$$

where ρ_{00}^{obs} is the value extracted from the acceptance and efficiency corrected $\cos\vartheta^*$ distribution of D^{*+} mesons.

The measured raw yields contain a mixture of prompt and non-prompt D^{*+} mesons. The extracted ρ_{00} parameters are therefore a linear combination of prompt ($\rho_{00}^{\text{prompt}}$) and non-prompt ($\rho_{00}^{\text{non-prompt}}$) contributions, and can be expressed as

$$\rho_{00} = f_{\text{prompt}} \cdot \rho_{00}^{\text{prompt}} + (1 - f_{\text{prompt}}) \cdot \rho_{00}^{\text{non-prompt}}, \quad (3.5)$$

where f_{prompt} is the fraction of prompt D^{*+} mesons in the raw yields. In order to evaluate this fraction, a data-driven method based on the sampling of the raw yield Y_i at different values of the BDT-output score related to the probability of being a non-prompt D^{*+} meson was adopted [39]. The BDT score related to the non-prompt D^{*+} meson probability was adopted rather than the one related to the prompt D^{*+} probability owing its more powerful discrimination of the two contributions. The f_{prompt} parameter can be computed by solving a system of equations that relate raw yields to the corrected yields of prompt (N_{prompt}) and non-prompt ($N_{\text{non-prompt}}$) D^{*+} mesons by the $(\text{Acc} \times \epsilon)$ factors. Each equation, obtained for a set of BDT selections i , can be expressed as

$$(\text{Acc} \times \epsilon)_{\text{prompt},i} \cdot N_{\text{prompt}} + (\text{Acc} \times \epsilon)_{\text{non-prompt},i} \cdot N_{\text{non-prompt}} - Y_i = \delta_i, \quad (3.6)$$

where δ_i is the residual originating from the uncertainties on Y_i , $(\text{Acc} \times \epsilon)_{\text{non-prompt},i}$, and $(\text{Acc} \times \epsilon)_{\text{prompt},i}$. The sets of selections were defined sampling the BDT-output score related to the probability of a candidate to be a non-prompt D^{*+} meson monotonically, to obtain n selections ordered in such a way that the i^{th} selected sample was completely included in the $(i - 1)^{\text{th}}$ one. The system of equations is then solved via a χ^2 minimisation procedure, which provides as output the corrected yields of prompt (N_{prompt}) and non-prompt ($N_{\text{non-prompt}}$) D^{*+} mesons and their covariance matrix. Finally, f_{prompt} was determined as

$$f_{\text{prompt},j} = \frac{(\text{Acc} \times \epsilon)_{\text{prompt},j} \cdot N_{\text{prompt}}}{(\text{Acc} \times \epsilon)_{\text{prompt},j} \cdot N_{\text{prompt}} + (\text{Acc} \times \epsilon)_{\text{non-prompt},j} \cdot N_{\text{non-prompt}}}. \quad (3.7)$$

where j denotes the set of selections used for the extraction of the ρ_{00} parameter, which is different from those adopted in the fraction evaluation. The uncertainty of $f_{\text{prompt},j}$ is computed considering the covariance matrix of N_{prompt} and $N_{\text{non-prompt}}$ obtained in the χ^2 -minimisation procedure.

The left panel of figure 3 shows an example of a raw yield extracted as a function of the BDT selection employed in the minimisation procedure for D^{*+} mesons with $4 < p_T < 6 \text{ GeV}/c$ in midcentral Pb–Pb collisions. The leftmost data point of the distribution is the raw yield corresponding to the loosest selection on the BDT output related to the candidate probability of being a non-prompt D^{*+} meson, while the rightmost one corresponds to the strictest selection, which is expected to preferentially select non-prompt D^{*+} mesons. The prompt and non-prompt components are represented by the red and blue filled histograms, respectively, while their sum is depicted by the green histogram. The f_{prompt} factor obtained in the 0–10% and 30–50% centrality classes for the selections adopted for the ρ_{00} extraction is reported in the right panel of the same figure. The fraction was evaluated for the total rapidity range $|y| < 0.8$, considering the limited size of the data sample and that no rapidity dependence is expected within the analysed range.

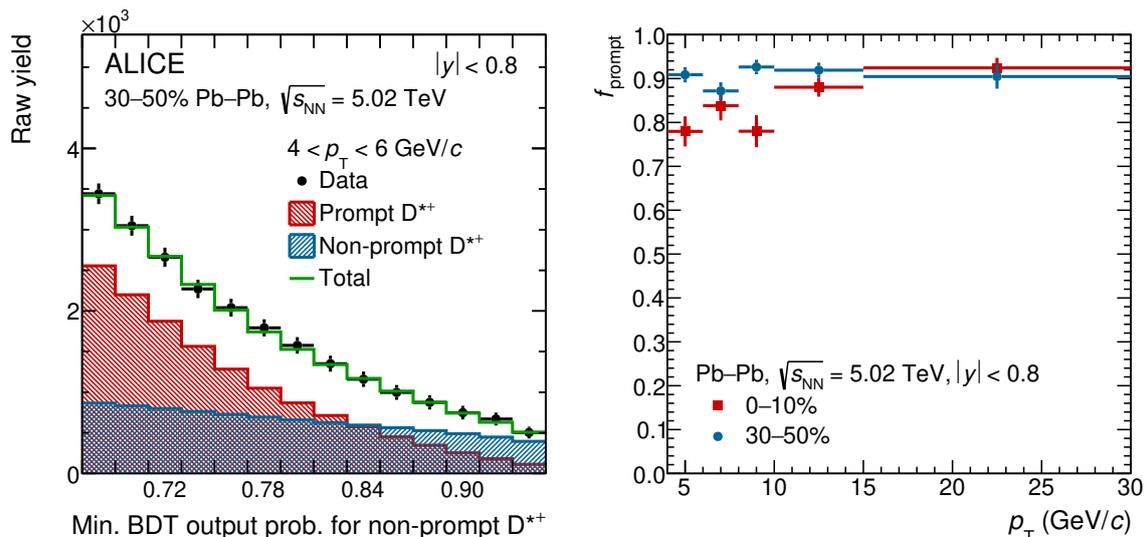


Figure 3. Left: raw yield as a function of the BDT selection and extracted contributions from prompt and non-prompt D^{*+} mesons with $4 < p_T < 6$ GeV/ c and $|y| < 0.8$ in the 30–50% centrality class. Right: measured fraction of prompt D^{*+} mesons as a function of p_T in the 0–10% and 30–50% centrality classes. Only the statistical uncertainties are reported.

Finally, to obtain the $\rho_{00}^{\text{prompt}}$ parameter from eq. (3.5) an assumption on the spin alignment of non-prompt D^{*+} mesons was necessary. The ρ_{00} parameter of non-prompt D^{*+} mesons was measured in pp collisions and found to be larger than $1/3$ with respect to the helicity axis, i.e. with respect to the direction of the D^{*+} momentum in the laboratory frame [26]. This result was understood as a consequence of the helicity conservation in scalar beauty-hadron decays. The measured ρ_{00} parameter of non-prompt D^{*+} mesons was found also to be well described by PYTHIA 8 + EVTGEN simulations. Given that the D^{*+} momentum (i.e. the helicity axis) in heavy-ion collisions is correlated with the direction of the reaction plane owing to the azimuthal anisotropies, due to the positive second-harmonic flow coefficient v_2 (elliptic flow), non-prompt D^{*+} mesons are expected to exhibit a ρ_{00} larger than $1/3$ with respect to the second-harmonic event plane ψ_2 . This implies a ρ_{00} lower than $1/3$ in the case of the quantisation axis considered in this analysis, which is orthogonal to ψ_2 and the beam axis. Following the study published in ref. [26], $\rho_{00}^{\text{non-prompt}}$ was then computed by performing PYTHIA 8 + EVTGEN simulations, in which an elliptic flow modulation was included. In particular, $v_2 = 0.05$ was used for the elliptic flow of non-prompt D^{*+} mesons, based on the recent publications of the measurement of non-prompt D^0 meson v_2 by the ALICE [40] and CMS [41] Collaborations.

Considering the high prompt fraction (right panel of figure 3) and the relatively small v_2 of non-prompt D^{*+} mesons, the procedure described above led to a maximum correction of about 0.01 in absolute value to the measured ρ_{00} to obtain the one of prompt D^{*+} mesons.

	0–10%		30–50%	
p_T (GeV/ c)	4–6	15–30	4–6	15–30
Signal yield	17%	13%	5%	3%
Tracking efficiency	6%	5%	4%	2%
BDT efficiency	5%	3%	5%	3%
Non-prompt subtraction	negl.	negl.	negl.	negl.
Total	19%	14%	8%	5%

Table 1. Summary of the relative systematic uncertainties on the ρ_{00} parameter of prompt D^{*+} mesons for representative p_T intervals in the 0–10% and 30–50% centrality classes.

4 Systematic uncertainties

The main sources of systematic uncertainties considered for the measurement of the ρ_{00} parameter of prompt D^{*+} mesons are i) the signal extraction, ii) the track reconstruction and selection efficiencies, iii) the BDT selection efficiency, and iv) the subtraction of the non-prompt contribution. The estimated values of the systematic uncertainties are summarised in table 1 for representative p_T intervals, together with the total systematic uncertainty obtained from the sum in quadrature of the different contributions. Since no significant difference in the systematic uncertainties evaluated in the two rapidity intervals was found, the same values were assigned to the measurements performed in the $|y| < 0.3$ and $0.3 < |y| < 0.8$ intervals.

The systematic uncertainty of the raw-yield extraction was evaluated by repeating the fit of the invariant-mass distribution varying the lower and upper limits of the fit range, leaving the Gaussian width free in the fits, and using an alternative functional form to describe the combinatorial background, namely $p_0(\Delta M - M_\pi)^{p_1}$, where p_0 and p_1 are free parameters. The values of systematic uncertainties range from 13% to 17% for central collisions, and 3% to 11% for midcentral collisions depending on p_T .

The systematic uncertainty associated to the track selection and reconstruction efficiency was evaluated by varying the track-quality selection criteria and comparing the different ρ_{00} parameters obtained. In particular, different requirements of number of space points for the track-reconstruction in the ITS and TPC were tested. The systematic uncertainty ranges between 3% and 8% for central collisions and 2% and 4% for midcentral collisions, depending on p_T .

The systematic uncertainty associated to the determination of the selection efficiency, arising from possible imperfections in the description of the decay topology or the detector resolution in the simulation, was estimated by using alternative sets of selections on the BDT-output score related to the probability of being background and repeating the ρ_{00} measurement. A systematic uncertainty ranging between 3% and 7% was assigned for central collisions, while an uncertainty between 3% and 5% for midcentral collisions was assigned.

The systematic uncertainty related to the subtraction of the non-prompt component has two contributions. The first one is related to the determination of the prompt fraction in the raw yield. Similarly to the previous source of systematic uncertainty, this is mainly related

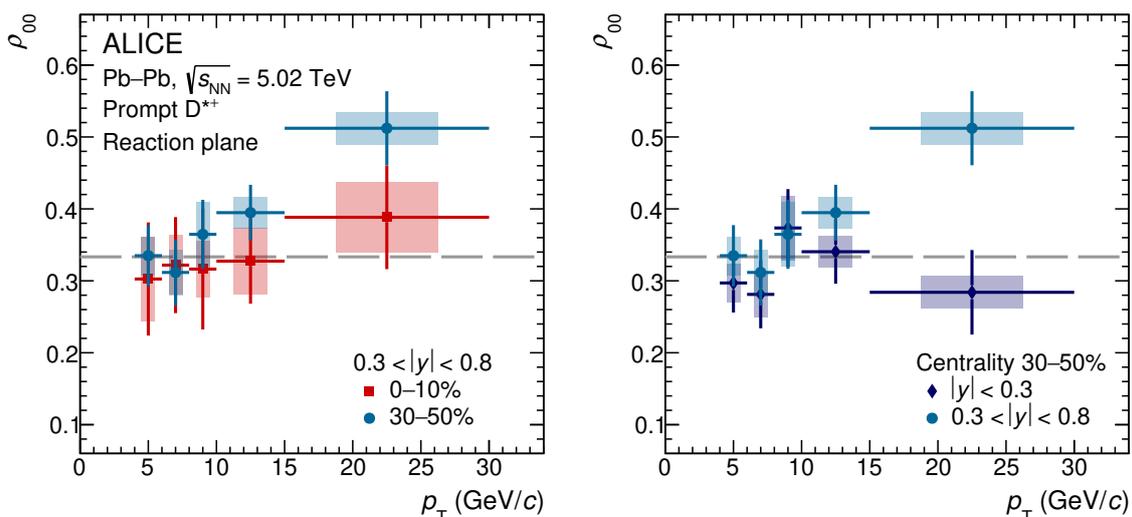


Figure 4. Left: the spin density matrix element ρ_{00} of prompt D^{*+} mesons as a function of p_T in the rapidity interval $0.3 < |y| < 0.8$ for central (0–10%) and midcentral (30–50%) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Right: ρ_{00} of prompt D^{*+} mesons as a function of p_T in the two rapidity intervals for midcentral (30–50%) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The measurements are carried out with respect to the direction perpendicular to the reaction plane. Statistical and systematic uncertainties are represented by bars and boxes, respectively.

to the description of the topological variables in the MC simulations used to determine the selection efficiencies of prompt and non-prompt D^{*+} mesons. Therefore, stricter and looser selections on the BDT score related to be a non-prompt D^{*+} meson, as well as different combinations of selections adopted to define the system of equations described in eq. (3.6), were tested. The second source of uncertainty instead originates from the assumption on the elliptic flow of non-prompt D^{*+} mesons. In this case, a value of $v_2 = 0.10$ was used alternatively to the default one of $v_2 = 0.05$. Both the effect of the f_{prompt} and v_2 variations were found to have a negligible effect on the ρ_{00} parameter for both centrality classes.

5 Results

The left panel of figure 4 shows the ρ_{00} parameter measured with respect to the direction orthogonal to the reaction plane for prompt D^{*+} mesons with $0.3 < |y| < 0.8$ as a function of p_T in central (0–10%) and midcentral (30–50%) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Vertical bars represent statistical uncertainties, while the filled boxes represent systematic uncertainties. The data points for central events are compatible with $1/3$ in the full p_T range. A hint of increasing trend with p_T is instead found for midcentral events, with a maximum deviation from $1/3$ in the $15 < p_T < 30$ GeV/ c interval of about 3.1σ , where σ is the sum in quadrature of statistical and systematic uncertainties. However, no significant deviation from $1/3$ is observed for D^{*+} mesons in the $|y| < 0.3$ interval even at high p_T , as reported in the right panel of figure 4.

The intriguing possible p_T and rapidity dependence of D^{*+} spin alignment measured at the LHC energies may be explained by a polarisation of early produced high- p_T charm quarks induced by the early magnetic field, which decreases slower in time as rapidity increases [23, 42]. In the thermal limit, there are currently no theory calculations based on vorticity and magnetic field that could lead to the observed values of vector-meson spin alignment. However, it is worth to note that the measured spin alignment of D^{*+} meson seems to be larger at very high p_T , where the charm quarks are less likely to be thermalised. In fact, a recent theory study based on rotational Brownian motion of heavy quarks in a QCD medium suggests that heavy quarks with higher p_T can retain a sizable polarisation originating from the initial magnetic field due to their shorter interaction time with the medium constituents [24]. In particular, a significant enhancement of charm-quark polarisation with p_T is predicted, with the magnitude of charm-quark polarisation depending on the spin-relaxation time of charm quarks. Moreover, the high value of spin alignment could have a different physical origin, e.g. local polarisation [14, 15], fluctuation of quark polarisation in turbulent colour fields [16], local spin correlation in the glasma phase [17], ϕ meson fields [21, 43], modification of vector-meson spectral function in thermal background [22]. Theory calculations based on ϕ meson field [21, 43] predict a non-trivial transverse momentum and rapidity dependence of the spin alignment. In particular, the p_T dependence of the spin alignment is correlated with the elliptic flow, therefore a significant positive spin alignment ($\rho_{00} > 1/3$) is expected at relatively forward rapidity. Similar rapidity and p_T dependence is also predicted by the theory calculation based on the holographic spin alignment [22] that incorporates the modification of the vector-meson spectral function for different spin modes in the presence of thermal background. It is important to notice that these calculations are valid only in the limit of a static medium and neglect the hydrodynamic expansion of the QGP. However, corrections due to the hydrodynamic expansion of the medium are expected to not have a significant impact for high-momentum partons, as discussed in ref. [44]. Although the possible rapidity dependence measured for the D^{*+} spin alignment is qualitatively similar to these theory calculations, these predictions are only available for flavourless vector mesons (ϕ and J/ψ). To compare D^{*+} spin alignment measurements with meson field theory calculations [21, 43], it is necessary to incorporate both the D^{*+} field and the fragmentation hadronisation mechanism into these models. This is because current calculations assume coalescence as the primary hadronisation process, while fragmentation is expected to dominate in the high- p_T region [45, 46]. Additionally, theoretical predictions [18] suggest that the fragmentation of polarised charm quarks could result in a ρ_{00} value larger than 1/3. This measurement will motivate new theoretical developments in the charm-hadron sector in order to understand the possible underlying physics mechanism of charm-hadron polarisation.

Figure 5 shows the comparison of the ρ_{00} parameter of prompt D^{*+} mesons in the rapidity interval $0.3 < |y| < 0.8$ compared with the one of inclusive J/ψ mesons measured in the $2.5 < y < 4$ rapidity interval in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the 30–50% centrality class [25]. Measurements of quarkonia polarisation are typically reported in terms of the λ_ϑ , λ_φ , and $\lambda_{\vartheta\varphi}$ parameters, which are extracted from the two-dimensional angular distribution of the two leptons (e^+e^- or $\mu^+\mu^-$) emerging from their decays as reported in refs. [25, 47–51].

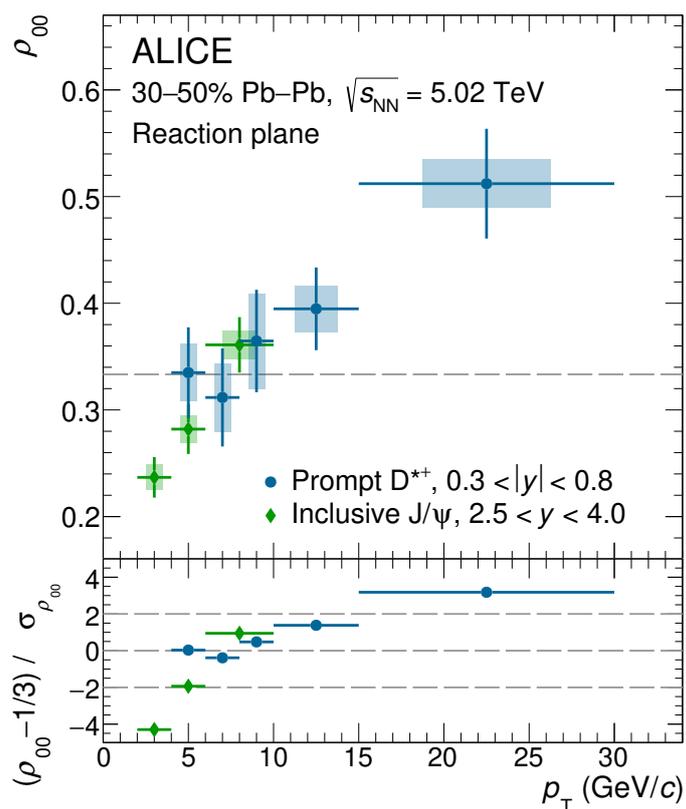


Figure 5. The spin density matrix element ρ_{00} of prompt D^{*+} mesons as a function of p_T in the rapidity interval $0.3 < |y| < 0.8$ compared to that of inclusive J/ψ mesons in the rapidity interval $2.5 < y < 4$ measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 30–50% centrality class. The bottom panel shows the deviation of the measurements from the null hypothesis ($\rho_{00} = 1/3$) in units of the total uncertainties $\sigma_{\rho_{00}}$.

In particular, the λ_{ϑ} parameter is related the ρ_{00} parameter via the following relation

$$\rho_{00} = \frac{1 - \lambda_{\vartheta}}{3 + \lambda_{\vartheta}}, \tag{5.1}$$

implying $\rho_{00} > 1/3$ if $\lambda_{\vartheta} < 0$ and viceversa. The bottom panel of the same figure shows the deviation of ρ_{00} from $\rho_{00} = 1/3$ in units of the total uncertainties σ . An evidence of $\rho_{00} < 1/3$ is found for inclusive J/ψ mesons at forward rapidity with $p_T < 4$ GeV/c in midcentral Pb–Pb collisions which is qualitatively in agreement with a recent theory calculation based on holographic spin alignment [22]. The measured ρ_{00} of prompt D^{*+} mesons in the rapidity range $0.3 < |y| < 0.8$ and the inclusive J/ψ at forward rapidity ($2.5 < y < 4$) are compatible within uncertainties in the overlapping p_T region ($4 < p_T < 10$ GeV/c) and seem to feature a common increasing trend with increasing p_T . However, in order to draw firm conclusions about a possible common dependence with p_T , proper theoretical guidance is needed.

6 Summary

In summary, the first measurement of prompt D^{*+} -meson spin alignment with respect to the direction orthogonal to the reaction plane at midrapidity in central (0–10%) and midcentral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been presented. An evidence of $\rho_{00} > 1/3$ for $p_T > 15$ GeV/ c in the $0.3 < |y| < 0.8$ range has been found for midcentral (30–50%) Pb–Pb collisions. The measured spin alignment seems to be more prominent at very high- p_T where charm quarks are expected to be produced much earlier and less likely to be thermalised. In order to understand any possible effect of early magnetic fields created in heavy-ion collisions on charm-quark polarisation, dedicated theory predictions of charm-quark polarisation and charm-hadron spin alignment are needed. From the experimental side, significant precision improvements for charm-hadron measurements are expected from the large datasets that are being collected by the ALICE Collaboration during the LHC Run 3 data-taking period, thanks to the upgrade of the experimental apparatus [52]. This will also allow for the extension of polarisation and spin alignment measurements of other charm-hadron species, such as Λ_c^+ baryons.

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References

- [1] ALICE collaboration, *The ALICE experiment: a journey through QCD*, *Eur. Phys. J. C* **84** (2024) 813 [[arXiv:2211.04384](https://arxiv.org/abs/2211.04384)] [[INSPIRE](#)].
- [2] F. Becattini, F. Piccinini and J. Rizzo, *Angular momentum conservation in heavy ion collisions at very high energy*, *Phys. Rev. C* **77** (2008) 024906 [[arXiv:0711.1253](https://arxiv.org/abs/0711.1253)] [[INSPIRE](#)].
- [3] P. Christakoglou, *Probing the magnetic field strength dependence of the chiral magnetic effect*, *Eur. Phys. J. C* **84** (2024) 290 [[arXiv:2308.02361](https://arxiv.org/abs/2308.02361)] [[INSPIRE](#)].
- [4] Y. Jiang, Z.-W. Lin and J. Liao, *Rotating quark-gluon plasma in relativistic heavy ion collisions*, *Phys. Rev. C* **94** (2016) 044910 [Erratum *ibid.* **95** (2017) 049904] [[arXiv:1602.06580](https://arxiv.org/abs/1602.06580)] [[INSPIRE](#)].
- [5] C.-H. Zhang et al., *Magnetic field evolution in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Sci. Rep.* **13** (2023) 21500 [[INSPIRE](#)].
- [6] Y.-G. Yang, R.-H. Fang, Q. Wang and X.-N. Wang, *Quark coalescence model for polarized vector mesons and baryons*, *Phys. Rev. C* **97** (2018) 034917 [[arXiv:1711.06008](https://arxiv.org/abs/1711.06008)] [[INSPIRE](#)].
- [7] U. Fano, *Description of States in Quantum Mechanics by Density Matrix and Operator Techniques*, *Rev. Mod. Phys.* **29** (1957) 74 [[INSPIRE](#)].
- [8] K. Schilling, P. Seyboth and G.E. Wolf, *On the Analysis of Vector Meson Production by Polarized Photons*, *Nucl. Phys. B* **15** (1970) 397 [Erratum *ibid.* **18** (1970) 332] [[INSPIRE](#)].
- [9] R. Snellings, *Elliptic Flow: A Brief Review*, *New J. Phys.* **13** (2011) 055008 [[arXiv:1102.3010](https://arxiv.org/abs/1102.3010)] [[INSPIRE](#)].
- [10] ALICE collaboration, *Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions*, *Phys. Rev. Lett.* **125** (2020) 012301 [[arXiv:1910.14408](https://arxiv.org/abs/1910.14408)] [[INSPIRE](#)].
- [11] STAR collaboration, *Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions*, *Nature* **614** (2023) 244 [[arXiv:2204.02302](https://arxiv.org/abs/2204.02302)] [[INSPIRE](#)].
- [12] F. Becattini et al., *Global hyperon polarization at local thermodynamic equilibrium with vorticity, magnetic field and feed-down*, *Phys. Rev. C* **95** (2017) 054902 [[arXiv:1610.02506](https://arxiv.org/abs/1610.02506)] [[INSPIRE](#)].
- [13] J.-P. Lv et al., *Global quark spin correlations in relativistic heavy ion collisions*, *Phys. Rev. D* **109** (2024) 114003 [[arXiv:2402.13721](https://arxiv.org/abs/2402.13721)] [[INSPIRE](#)].
- [14] J.-H. Gao, *Helicity polarization in relativistic heavy ion collisions*, *Phys. Rev. D* **104** (2021) 076016 [[arXiv:2105.08293](https://arxiv.org/abs/2105.08293)] [[INSPIRE](#)].
- [15] X.-L. Xia, H. Li, X.-G. Huang and H. Zhong Huang, *Local spin alignment of vector mesons in relativistic heavy-ion collisions*, *Phys. Lett. B* **817** (2021) 136325 [[arXiv:2010.01474](https://arxiv.org/abs/2010.01474)] [[INSPIRE](#)].
- [16] B. Müller and D.-L. Yang, *Anomalous spin polarization from turbulent color fields*, *Phys. Rev. D* **105** (2022) L011901 [Erratum *ibid.* **106** (2022) 039904] [[arXiv:2110.15630](https://arxiv.org/abs/2110.15630)] [[INSPIRE](#)].
- [17] A. Kumar, B. Müller and D.-L. Yang, *Spin alignment of vector mesons by glasma fields*, *Phys. Rev. D* **108** (2023) 016020 [[arXiv:2304.04181](https://arxiv.org/abs/2304.04181)] [[INSPIRE](#)].
- [18] Z.-T. Liang and X.-N. Wang, *Spin alignment of vector mesons in non-central A+A collisions*, *Phys. Lett. B* **629** (2005) 20 [[nuc1-th/0411101](https://arxiv.org/abs/nuc1-th/0411101)] [[INSPIRE](#)].

- [19] X.-L. Sheng, L. Oliva and Q. Wang, *What can we learn from the global spin alignment of ϕ mesons in heavy-ion collisions?*, *Phys. Rev. D* **101** (2020) 096005 [Erratum *ibid.* **105** (2022) 099903] [[arXiv:1910.13684](#)] [[INSPIRE](#)].
- [20] X.-L. Sheng et al., *Spin Alignment of Vector Mesons in Heavy-Ion Collisions*, *Phys. Rev. Lett.* **131** (2023) 042304 [[arXiv:2205.15689](#)] [[INSPIRE](#)].
- [21] X.-L. Sheng, S. Pu and Q. Wang, *Momentum dependence of the spin alignment of the ϕ meson*, *Phys. Rev. C* **108** (2023) 054902 [[arXiv:2308.14038](#)] [[INSPIRE](#)].
- [22] X.-L. Sheng et al., *Holographic spin alignment for vector mesons*, *Phys. Rev. D* **110** (2024) 056047 [[arXiv:2403.07522](#)] [[INSPIRE](#)].
- [23] S.K. Das et al., *Directed Flow of Charm Quarks as a Witness of the Initial Strong Magnetic Field in Ultra-Relativistic Heavy Ion Collisions*, *Phys. Lett. B* **768** (2017) 260 [[arXiv:1608.02231](#)] [[INSPIRE](#)].
- [24] S. Dey and A. Jaiswal, *Rotational Brownian motion and heavy quark polarization in QCD medium*, [arXiv:2502.20352](#) [[INSPIRE](#)].
- [25] ALICE collaboration, *Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC*, *Phys. Rev. Lett.* **131** (2023) 042303 [[arXiv:2204.10171](#)] [[INSPIRE](#)].
- [26] ALICE collaboration, *First measurement of prompt and non-prompt D^{*+} vector meson spin alignment in pp collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett. B* **846** (2023) 137920 [[arXiv:2212.06588](#)] [[INSPIRE](#)].
- [27] ALICE collaboration, *The ALICE experiment at the CERN LHC*, *2008 JINST* **3** S08002 [[INSPIRE](#)].
- [28] ALICE collaboration, *Performance of the ALICE Experiment at the CERN LHC*, *Int. J. Mod. Phys. A* **29** (2014) 1430044 [[arXiv:1402.4476](#)] [[INSPIRE](#)].
- [29] ALICE collaboration, *Centrality Dependence of the Charged-Particle Multiplicity Density at Midrapidity in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Rev. Lett.* **116** (2016) 222302 [[arXiv:1512.06104](#)] [[INSPIRE](#)].
- [30] I. Selyuzhenkov and S. Voloshin, *Effects of non-uniform acceptance in anisotropic flow measurement*, *Phys. Rev. C* **77** (2008) 034904 [[arXiv:0707.4672](#)] [[INSPIRE](#)].
- [31] PARTICLE DATA GROUP collaboration, *Review of particle physics*, *Phys. Rev. D* **110** (2024) 030001 [[INSPIRE](#)].
- [32] T. Chen and C. Guestrin, *XGBoost: A Scalable Tree Boosting System*, [arXiv:1603.02754](#) [[DOI:10.1145/2939672.2939785](#)] [[INSPIRE](#)].
- [33] L. Barioglio et al., *hipe4ml/hipe4ml*, (2021), [DOI:10.5281/zenodo.5070132](#).
- [34] X.-N. Wang and M. Gyulassy, *HIJING: A Monte Carlo model for multiple jet production in $p p$, $p A$ and $A A$ collisions*, *Phys. Rev. D* **44** (1991) 3501 [[INSPIRE](#)].
- [35] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
- [36] P. Skands, S. Carrazza and J. Rojo, *Tuning PYTHIA 8.1: the Monash 2013 Tune*, *Eur. Phys. J. C* **74** (2014) 3024 [[arXiv:1404.5630](#)] [[INSPIRE](#)].
- [37] R. Brun et al., *GEANT Detector Description and Simulation Tool*, CERN-W5013 (1994) [[DOI:10.17181/CERN.MUHF.DMJ1](#)] [[INSPIRE](#)].

- [38] A.H. Tang et al., *Practical considerations for measuring global spin alignment of vector mesons in relativistic heavy ion collisions*, *Phys. Rev. C* **98** (2018) 044907 [Erratum *ibid.* **107** (2023) 039901] [[arXiv:1803.05777](#)] [[INSPIRE](#)].
- [39] ALICE collaboration, *Measurement of beauty and charm production in pp collisions at $\sqrt{s} = 5.02$ TeV via non-prompt and prompt D mesons*, *JHEP* **05** (2021) 220 [[arXiv:2102.13601](#)] [[INSPIRE](#)].
- [40] ALICE collaboration, *Measurement of non-prompt D^0 -meson elliptic flow in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Eur. Phys. J. C* **83** (2023) 1123 [[arXiv:2307.14084](#)] [[INSPIRE](#)].
- [41] CMS collaboration, *Measurements of azimuthal anisotropy of nonprompt D^0 mesons in PbPb collisions at $s_{NN}=5.02$ TeV*, *Phys. Lett. B* **850** (2024) 138389 [[arXiv:2212.01636](#)] [[INSPIRE](#)].
- [42] A. Dubla, U. Gürsoy and R. Snellings, *Charge-dependent flow as evidence of strong electromagnetic fields in heavy-ion collisions*, *Mod. Phys. Lett. A* **35** (2020) 2050324 [[arXiv:2009.09727](#)] [[INSPIRE](#)].
- [43] X.-L. Sheng et al., *Relativistic spin dynamics for vector mesons*, *Phys. Rev. D* **109** (2024) 036004 [[arXiv:2206.05868](#)] [[INSPIRE](#)].
- [44] J. Xu, J. Liao and M. Gyulassy, *Bridging Soft-Hard Transport Properties of Quark-Gluon Plasmas with CUJET3.0*, *JHEP* **02** (2016) 169 [[arXiv:1508.00552](#)] [[INSPIRE](#)].
- [45] S. Plumari et al., *Charmed Hadrons from Coalescence plus Fragmentation in relativistic nucleus-nucleus collisions at RHIC and LHC*, *Eur. Phys. J. C* **78** (2018) 348 [[arXiv:1712.00730](#)] [[INSPIRE](#)].
- [46] A. Beraudo et al., *In-medium hadronization of heavy quarks and its effect on charmed meson and baryon distributions in heavy-ion collisions*, *Eur. Phys. J. C* **82** (2022) 607 [[arXiv:2202.08732](#)] [[INSPIRE](#)].
- [47] ALICE collaboration, *J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. Lett.* **108** (2012) 082001 [[arXiv:1111.1630](#)] [[INSPIRE](#)].
- [48] ALICE collaboration, *Measurement of the inclusive J/ψ polarization at forward rapidity in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J. C* **78** (2018) 562 [[arXiv:1805.04374](#)] [[INSPIRE](#)].
- [49] LHCb collaboration, *Measurement of J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV*, *Eur. Phys. J. C* **73** (2013) 2631 [[arXiv:1307.6379](#)] [[INSPIRE](#)].
- [50] CMS collaboration, *Measurement of the Prompt J/ψ and $\psi(2S)$ Polarizations in pp Collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett. B* **727** (2013) 381 [[arXiv:1307.6070](#)] [[INSPIRE](#)].
- [51] ALICE collaboration, *First measurement of quarkonium polarization in nuclear collisions at the LHC*, *Phys. Lett. B* **815** (2021) 136146 [[arXiv:2005.11128](#)] [[INSPIRE](#)].
- [52] ALICE collaboration, *ALICE upgrades during the LHC Long Shutdown 2, 2024* *JINST* **19** P05062 [[arXiv:2302.01238](#)] [[INSPIRE](#)].
- [53] ALICE collaboration, *Data for “First measurement of D^{*+} vector meson spin alignment in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”*, <https://doi.org/10.17182/hepdata.165763>.

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