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Vector meson polarization measurements in pp and Pb–Pb collisions with ALICE

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Polarization measurements are important for understanding the vector mesons production mechanisms in proton proton (pp) and heavy-ion collisions. Quarkonium measurements in pp collision are crucial to constrain both perturbative and non-perturbative aspects of QCD calculations. The study of quarkonia polarization in pp collisions represents a powerful tool to discriminate among different QCD-based production models. Furthermore, quarkonium polarization measurement in pp collisions can also provide a reference for investigating the fate of charmonium in the quark-gluon plasma (QGP) formed in nucleus-nucleus collisions. When considering heavy-ion collisions, vector meson polarization, as charmed hadrons and quarkonia could, also be used to investigate the characteristics of the QGP. Recently, it has been shown that light vector mesons produced in Pb–Pb collisions are polarized, an effect likely due to the presence of a large angular momentum of the strongly interacting system produced in non-central heavy-ion collisions. It has also been conjectured that vector mesons could be polarized by the strong magnetic field generated in the early phase of the evolution of the system.

In this contribution, the recent ALICE measurements of J/ψ and D^* polarization with respect to the reaction plane in $\sqrt{s_{NN}} = 5.02$ TeV collisions at forward and midrapidity are presented, respectively. The $\Upsilon(1S)$ polarization with respect to the Collins-Soper and Helicity reference frames in pp collisions at $\sqrt{s} = 13$ TeV are reported.

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1. Introduction

Quarkonia has been discovered for a long time, but its production mechanism still remains a challenge for the fundamental theory of quantum chromodynamics (QCD) [1]. According to the current theoretical framework of non-relativistic QCD (NRQCD) [2], the production of heavy quarkonium is characterized in two distinct processes. Firstly, a heavy quark-antiquark pair is generated in the early stage of the collision via hard partons scattering. Secondly, the $Q\bar{Q}$ pairs, produced in either a colour-singlet or colour-octet state, undergo non-perturbative evolution, and transform into a bound state [3–5]. The color-singlet model calculations demonstrate a good agreement with the measured production cross sections, but fails to describe the polarization of J/ψ. Leading-order color-singlet calculations predict a transverse polarization while next-to-leading-order (NLO) calculations predict a longitudinal polarization [6]. Therefore, measurements of the polarization of the quarkonium state are critical for distinguishing between different theoretical approaches of the quarkonia production mechanisms. In a two-body decays, the polarization can be measured through the study of the angular distributions of the decay products in different reference frames, as describes in Eq. 1. The λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ are the polarization parameters, which can be determined by the fit of the angular distributions of the decay products, as described in Ref. [7]. The spin alignment of the spin 1 vector meson can also be described by a 3 × 3 Hermitian spin-density matrix. The matrix elements can be obtained by measuring the angular distributions of the decay products of the vector mesons with respect to a quantization axis. The angle denoted as θ is that defined by one of the decay daughters of the vector meson in the rest frame of the vector meson with respect to the quantization axis. In general, the angular distribution for vector mesons is expressed as in Eq. 2 [8]. The diagonal elements, labeled as ρ_{11}, ρ_{00}, and ρ_{-1-1}, indicate the probabilities for spin component along a quantization axis to have values of 1, 0, and -1, respectively. The ρ_{00} is the only parameter that can be measured for the indication of the vector mesons spin alignment [9, 10], where ρ_{00} value equal to 1/3 corresponds to no polarization.

$$\frac{\mathrm{d}^2 \mathrm{N}}{\mathrm{d}\cos\theta \mathrm{d}\phi} \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi\right) \quad (1)$$

$$\frac{\mathrm{dN}}{\mathrm{d}\cos\theta} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta \quad (2)$$

In heavy-ion collisions, a hot and dense state of matter known as quark-gluon plasma (QGP) is created. This provides an ideal environment to study non-perturbative QCD, the theory that describes the strong interaction between quarks and gluons [5, 11–14]. In non-central heavy-ion collisions, significant orbital angular momentum and strong magnetic field are expected to be generated [15–18]. This orbital angular momentum and magnetic field might potentially polarize the quarks, and this polarization can be transferred to the vector mesons through the hadronization process.

Heavy quarks, specifically charm and beauty, serve as excellent probes for studying the QGP. They are predominantly produced through initial hard scatterings of the heavy-ion collisions, which allows them to experience the strong electromagnetic field generated early on, as well as the entire evolution of the QGP [3, 12–14]. The measurements of spin alignment in particles such as Υ(1S),

D^* and J/ψ is crucial for understanding the vorticity and strong electromagnetic fields produced in non-central heavy-ion collisions, the QGP evolution, and the hadronization processes [16, 19].

2. Results

The measurements of $\Upsilon(1S)$ and J/ψ polarization and D^* spin alignment are carried out by the ALICE detector, whose detailed description can be found in Refs. [20, 21] . The $\Upsilon(1S)$ and the inclusive J/ψ are reconstructed in the $\mu^+\mu^-$ decay channel at forward rapidity ($2.5 < y < 4$), while the D^* is reconstructed via the $D^{*+} \to D^0 (\to K^-\pi^+)\, \pi^+$ decay channel at midrapidity ($|y| < 0.9$).

The $\Upsilon(1S)$ polarization parameters λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ are studied as a function of transverse momentum (p_T) in pp collisions at $\sqrt{s}$ =13 TeV and at forward rapidity. The measurements in Helicity (left) and Collins-Soper (right) reference frames are shown in Fig. 1, and the results are compared with the similar measurements in pp collisions at $\sqrt{s}$ = 8 TeV by the LHCb Collaboration [22]. The values of the $\Upsilon(1S)$ polarization parameters λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ are consistent with zero in both reference frames. These results are in agreement within the uncertainties with the LHCb measurement in pp collisions at $\sqrt{s}$ = 8 TeV [22].

The first measurement of D^* spin alignment with respect to the reaction plane in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV is shown in Fig. 2. In the left panel of Fig. 2, the ρ_{00} is shown as a function of the rapidity in semicentral collisions of 30-50% centrality at $15 < p_T < 30$ GeV/c interval. It should be noted that a larger deviation with respect to 1/3 is observed for large rapidities ($0.3 < |y| < 0.8$) than at central rapidity ($|y| < 0.3$). In the right panel of the Fig. 2, the ρ_{00} is shown as a function of p_T in the central (0–10%) and semicentral (30–50%) collisions for $0.3 < |y| < 0.8$. The ρ_{00} values are compatible with 1/3 for 0–10% centrality interval, and increases above 1/3 at the high p_T ($15 < p_T < 30$ GeV/c) for 30–50% centrality class.

The spin alignment of inclusive J/ψ production with respect to the event plane is measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV via the dimuon decay channel at forward rapidity [23]. In the left panel of Fig. 3, the p_T-integrated λ_θ parameters for different centrality classes are presented. A significant non-zero spin alignment is observed in central and semicentral collisions, particularly in the 40−60% centrality interval, where a 3.5σ effect is observed. The right panel of Fig. 3 displays the p_T-dependence of λ_θ in central (0−20%) and semicentral (30−50%) collisions. A non-zero polarization is observed for $2 < p_T < 4$ GeV/c in the 30−50% centrality interval with a significance of 3.9σ when considering the total uncertainties.

Figure 4 displays the p_T-differential ρ_{00} parameter comparisons between inclusive J/ψ and prompt D^* in the centrality class 30−50%. A significant non-zero polarization is observed at low p_T for J/ψ, falling below 1/3, and following a smooth transition from J/ψ to D^* in the intermediate overlapping p_T range, leading to values greater than 1/3 at the high p_T. The increasing trend of ρ_{00} as a function of the p_T agrees with predictions of two different hadronization mechanisms [15]. ρ_{00} lower than 1/3 suggests that recombination might be the dominant hadronization mechanism at low-p_T ($2 < p_T < 5$ GeV/c). Conversely, at high-p_T ($10 < p_T < 30$ GeV/c) the ρ_{00} values greater than 1/3 indicates that fragmentation could play a significant role.

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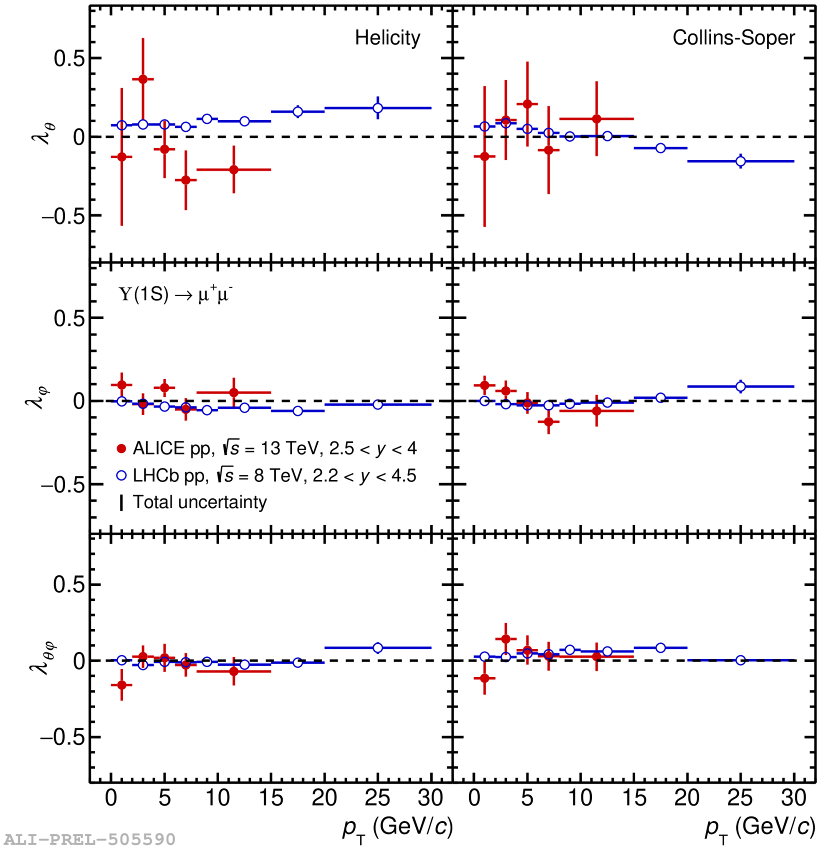

Figure 1: $\Upsilon(1S)$ polarization parameters as a function of p_T in pp collisions at $\sqrt{s}$ =13 TeV and at the forward rapidity, compared with results obtained in pp collisions at $\sqrt{s}$ = 8 TeV by LHCb [22]. The left and right panels shows the polarization parameters measured in the Helicity and Collins-Soper reference frames, respectively.

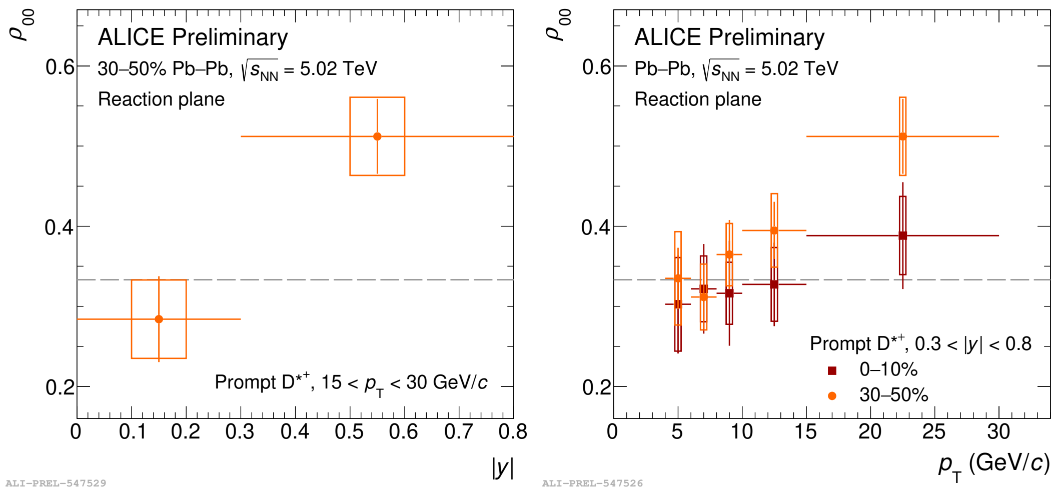

Figure 2: Rapidity (left) and p_T-dependence (right) of the prompt D^* meson spin alignment parameters ρ_{00} in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and at midrapidity.

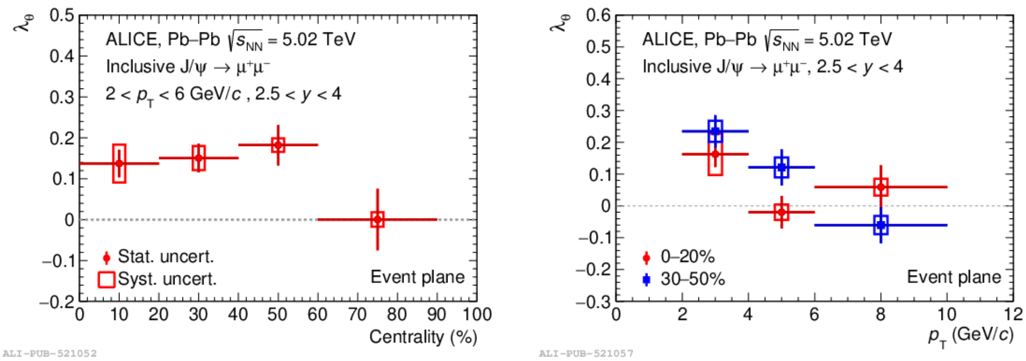

Figure 3: Centrality (left) and p_T-dependence (right) of the of inclusive J/ψ λ_θ spin alignment parameters with respect to the reaction plane in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV at forward rapidity [23].

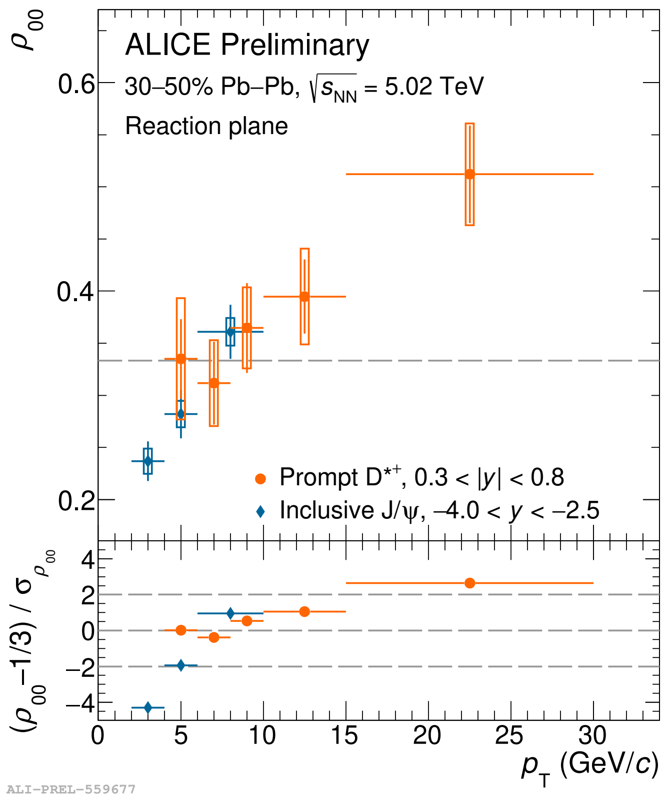

Figure 4: The polarization parameter ρ_{00} of inclusive J/ψ and prompt D* with respect to the reaction plane are measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in semicentral collisions at forward [23] and midrapidity, respectively.

3. Summary and outlook

In this contribution, the recent measurements of J/ψ, $\Upsilon(1S)$ and D^* polarization are presented in pp and Pb–Pb collisions. The $\Upsilon(1S)$ polarization parameters λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ in pp collisions are all compatible with zero within uncertainties in both Helicity and Collins-Soper reference frames. The first measurement of inclusive J/ψ polarization with respect to the event plane is shown as a function of centrality and p_T in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV at forward rapidity. A small but significant polarization effect, reaching 3.9σ for $2 < p_T < 4$ GeV/c in the 30−50% centrality interval, is reported. The spin density matrix element of prompt D^* is measured with respect to the reaction plane in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV at midrapidity. A large deviation with respect to 1/3 is observed for larger rapidities ($0.3 < |y| < 0.8$) than at central rapidity($|y| < 0.3$), the ρ_{00} follows an increasing trend as a function of p_T for 30–50% centrality class. The p_T-differential polarization parameters ρ_{00} are compared between inclusive J/ψ and prompt D^* in centrality class 30−50%, and an interesting continuity among the two results is observed.

The precision of existing measurements will be improved with the upgraded detectors and thanks to the larger data sample that will be collected. This will allow to measure precisely the J/ψ polarization also at midrapidity in the dielectron channel. Additionally, the newly installed MFT and upgraded ITS will enable distinguishing between prompt and non-prompt charmonium polarization at forward rapidity.

4. Acknowledgement

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