VECTOR MESONS POLARIZATION IN Pb–Pb AND *pp* COLLISIONS WITH ALICE*

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Polarization and spin-alignment measurements represent an important tool for the understanding of particle-production mechanisms occurring in proton–proton collisions. When considering heavy-ion collisions, quarkonium polarization could also be used to investigate the characteristics of the hot and dense medium (quark–gluon plasma) created at LHC energies. In ALICE, this observable was extracted for the first time in Pb–Pb collisions and a significant difference with respect to a corresponding measurement in *pp* collisions by the LHCb was found. This discrepancy could be related to the modification of the J/ψ feed-down fractions, due to the suppression of the excited charmonium states in the QGP, but also to the contribution of the regenerated J/ψ in the low transverse momentum region. Moreover, it has been hypothesized that quarkonium states could be polarized by the strong magnetic field, generated in the early phase of the evolution of the system, and by the large angular momentum of the medium in non-central heavy-ion collisions. This kind of information can be assessed by defining an *ad hoc* reference frame where the quantization axis is orthogonal to the event plane of the collision. In this contribution, the recent result of J/ψ polarization with respect to the event plane in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV will be presented. The p_{T}-differential measurement is performed at forward rapidity ($2.5 < y < 4$) with the ALICE muon spectrometer and the results will be shown for different centrality classes. The preliminary measurement of the $\Upsilon(1S)$ and D^{*+} polarization in *pp* collisions at $\sqrt{s} = 13$ TeV as a function of the transverse momentum will also be discussed.

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1. Introduction

The spin alignment of a particle with respect to a chosen direction represents an important test ground for our current knowledge of the mechanisms at work in heavy-ion collisions. In the following, we will refer to this observable as 'polarization', as usually done in quarkonium physics. In *pp* collisions, polarization is mainly studied in order to constrain the quarkonium production mechanism, since different theoretical models are providing different predictions for this observable [1, 2]. Moreover, vector mesons polarization in nucleus–nucleus collisions may be sensitive to the quark–gluon plasma (QGP) formation via the suppression [3] and regeneration [4] mechanisms, while in parallel, the large magnetic field [5] and angular momentum [6] postulated in non-central collisions may impact the observed spin alignment. Therefore, quarkonia on one side and open heavy-flavor hadrons on the other provide a unique opportunity to explore these effects with different time and energy scales. From an experimental point of view, the polarization is measured by determining the angular distributions of the decay products, which obey the following functional shape for a two-body decay:

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

where θ and ϕ are the polar and azimuthal angles, formed by the direction of the daughter particle and the quantization axis [7]. This distribution depends on the polarization parameters λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$. If all of them are null, the angular distribution is isotropic. If λ_θ is equal to $+1$ or -1 ($\lambda_\phi, \lambda_{\theta\phi} = 0$), the anisotropy of the distribution is maximal and it corresponds to the scenario of transverse or longitudinal polarization, respectively. Alternatively, a single differential functional shape can be used that factorizes the dependence on the spin density matrix element ρ_{00} [8]

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

where ρ_{00} defines the probability to find a vector meson in the spin state zero and corresponds to 1/3 in the absence of spin alignment.

2. $\Upsilon(1S)$ polarization in *pp* collisions at $\sqrt{s} = 13$ TeV

The ALICE detector, whose detailed description can be found in Ref. [9], performed the first measurement of the $\Upsilon(1S)$ polarization in *pp* collisions at $\sqrt{s} = 13$ TeV. Results are given using two different reference frames, namely the helicity and Collins–Soper. For the former, the quarkonium momentum direction in the center-of-mass of the collision is chosen as quantization axis, while for the Collins–Soper frame, the quantization axis is the bisector of the angle formed by the two colliding beams in the quarkonium rest frame. As shown in Fig. 1, all the polarization parameters are compatible with zero within uncertainties, with no clear trend as a function of the transverse momentum ($p_{\rm T}$). The result is also compatible with the same measurement performed by the LHCb Collaboration at $\sqrt{s} = 8$ TeV [11], pointing to no sizeable polarization measured for the $\varUpsilon(1S)$ regardless of the center-of-mass energy. Finally, these measurements are qualitatively in agreement with the expectations from NLO NRQCD, as shown in Ref. [12].

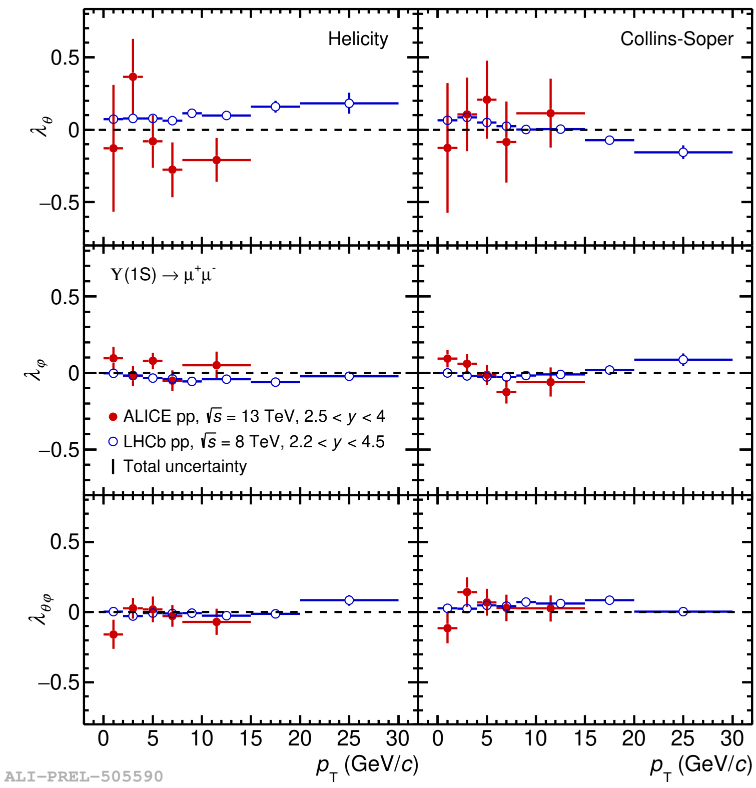

Fig. 1. The $\varUpsilon(1S)$ polarization parameters ($\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$) as a function of $p_{\rm T}$, measured by the ALICE Collaboration in *pp* collisions at $\sqrt{s} = 13$ TeV and at forward rapidity ($2.5 < y < 4$). The results are compared with the corresponding measurement performed by the LHCb Collaboration in *pp* collisions at $\sqrt{s} = 8$ TeV for $2.2 < y < 4.5$ [11]. The vertical bars are the sum in quadrature of systematic and statistical uncertainties.

3. D^{*+} polarization in pp collisions at $\sqrt{s} = 13$ TeV

The spin alignment of the D^{*+} is evaluated by the ALICE experiment for the first time at the LHC. The measurement, shown in Fig. 2, is performed separately for the prompt (from charm quark hadronization) and non-prompt (from bottom quark and following b-hadron weak decay) D^{*+}. The ρ_{00} parameter is found to be $\sim 1/3$ and greater than $1/3$ for the two components, respectively. The latter is interpreted as a consequence of the helicity conservation in the decay of a scalar beauty meson to a vector meson. Both results, obtained in the helicity reference frame, are in agreement with PYTHIA 8+EvtGen [13, 14].

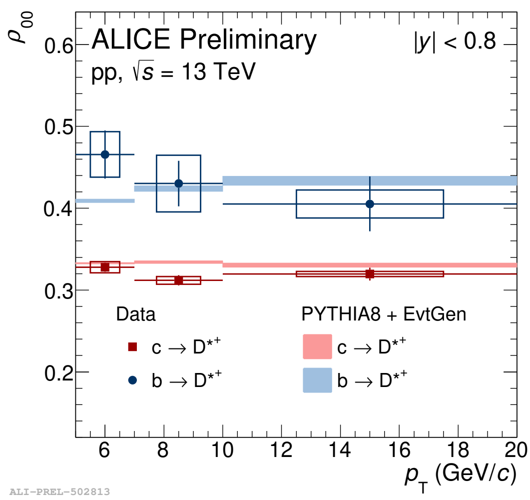

Fig. 2. (Color online) Measurement of D^{*+} ρ_{00} parameter in pp collisions at $\sqrt{s} = 13$ TeV and at midrapidity ($|y| < 0.8$). The prompt (red/gray) and non-prompt (blue/black) components are shown separately. The vertical bars represent the statistical uncertainties, while the boxes correspond to the systematic uncertainties. Results are compared with the predictions from PYTHIA 8+EvtGen [13, 14].

4. J/ψ polarization with respect to the event plane in Pb–Pb collisions

J/ψ polarization has been measured by the ALICE Collaboration in heavy-ion collisions in the helicity and Collins–Soper reference frames [10], and the measurement has been recently extended to a reference frame where the quantization axis corresponds to the direction orthogonal to the event plane (*i.e.* the plane identified by the impact parameter of the collision and the beam axis) [15]. The latter allows one to investigate potential effects related to the magnetic field due to the spectator nucleons [5] and the large angular momentum associated with the rotation of the medium produced in the collision [6]. The results shown in Fig. 3 exhibit a maximum deviation of $\sim 3.9\sigma$ with respect to $\lambda_\theta = 0$ in semi-central (30–50%) collisions for $2 < p_{\mathrm{T}} < 4$ GeV/c. This behavior is qualitatively in agreement with the one observed for light vector mesons (K^{*0} and ϕ) [16], even if the absence of theoretical predictions for the moment prevents from drawing a definitive conclusion on the mechanism responsible for the observed non-zero quarkonium polarization.

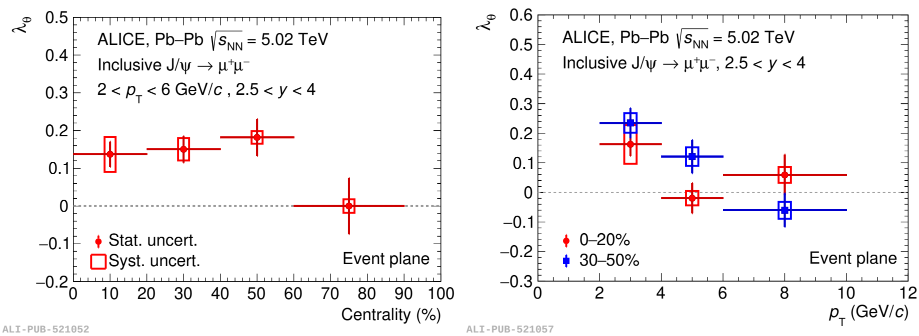

Fig. 3. Centrality (left panel) and p_{T} dependence (right panel) of λ_θ for the J/ψ measured with respect to the axis orthogonal to the event plane in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the forward rapidity region ($2.5 < y < 4$) [15]. The vertical bars represent the statistical uncertainties, while the boxes correspond to the systematic uncertainties.

5. Summary and conclusions

Vector meson polarization has been investigated by the ALICE Collaboration. For the $\Upsilon(1S)$ and prompt D^{*+}, the polarization parameters in *pp* collisions are compatible with zero, in agreement with theoretical models and Monte Carlo generators. This set of results represents an important baseline for future measurements in heavy-ion collisions. In parallel, the non-prompt D^{*+} exhibits a value of $\rho_{00} > 1/3$, in agreement with the expectations of helicity conservation in the decay of scalar mesons to vector mesons. Finally, the first measurement of the J/ψ polarization with respect to an axis orthogonal to the event plane has been performed, showing a significant ($\sim 3.9\sigma$) deviation with respect to $\lambda_\theta = 0$ for $2 < p_{\mathrm{T}} < 4$ GeV/c in the 30–50% centrality class. Even if a complete picture of polarization in hadronic collisions is for the moment missing, these recent results will contribute to expanding this field of research and to stimulating further theoretical developments.

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