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## Measurement of the $J/\psi$ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC

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We study the polarization of inclusive  $J/\psi$  produced in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV at the LHC in the dimuon channel, via the measurement of the angular distribution of its decay products. We perform the study in the rapidity region  $2.5 < y < 4$ , for three transverse momentum intervals ( $2 < p_T < 4$ ,  $4 < p_T < 6$ ,  $6 < p_T < 10$  GeV/ $c$ ) and as a function of the centrality of the collision for  $2 < p_T < 6$  GeV/ $c$ . For the first time, the polarization is measured with respect to the event plane of the collision, by considering the angle between the positive-charge decay muon in the  $J/\psi$  rest frame and the axis perpendicular to the event-plane vector in the laboratory system. A small transverse polarization is measured, with a significance reaching  $3.9\sigma$  at low  $p_T$  and for intermediate centrality values. The polarization could be connected with the behavior of the quark-gluon plasma, formed in Pb-Pb collisions, as a rotating fluid with large vorticity, as well as with the existence of a strong magnetic field in the early stage of its formation.

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Quarkonia, bound states of a heavy quark-antiquark pair, have been studied for a long time because they give access to several features of the strong interaction that can be investigated with various complementary approaches (see Refs. [1,2] for comprehensive reviews). Calculations based on the quantum chromodynamics (QCD) theory formulated on a discrete lattice [3] can reproduce the rich spectroscopy of the various states corresponding to different radial and angular excitations of the quarkonium wave function. The nonrelativistic QCD (NRQCD) approach [4] represents the most advanced tool for our understanding of quarkonium production in proton-proton collisions and is able to reproduce the measured cross sections for most states. The produced quarkonia may also exhibit polarization, defined as the alignment of the particle spin with respect to a chosen axis [5]. The polarization can be calculated in the framework of NRQCD, and although for some states discrepancies between theory and experiment persist until today, a reasonable understanding of quarkonium production and polarization has been reached [6–8]. Other approaches, such as the improved color evaporation model [9], are shown to reproduce quarkonium measurements at collider energies fairly well.

Quarkonium states may also be used as a probe of the environment in which they are created or they traverse during their evolution. Their binding energy and, more generally, their spectral functions may be altered [10,11] due to the presence of a quark-gluon plasma (QGP), a high energy-density state of strongly interacting matter formed in ultrarelativistic heavy-ion collisions and currently studied at RHIC and the LHC (at center-of-mass energies per nucleon-nucleon collision  $\sqrt{s_{NN}}$  up to 0.2 and 5.02 TeV, respectively). These hot matter effects may lead to the dissociation or prevent the formation of the bound  $q\bar{q}$  state. Furthermore, charmonia can also be significantly regenerated in the QGP phase and/or when the QGP hadronizes [12,13], in particular, when the initial multiplicity of produced charm quarks is large (e.g.,  $> 10^2$  for central Pb-Pb collisions at the LHC). Experimental results [14–17] have by now confirmed this picture.

In addition to the quarkonium yield modifications, the polarization of surviving quarkonia might be altered because of other specific features of the QGP environment. In particular, the fast motion of the charges of the nuclei can produce a magnetic field oriented perpendicular to the reaction plane, defined by the vector of the impact parameter of the collision and the beam direction, possibly exceeding  $10^{20}$  Gauss at LHC energies [18–20]. The maximum value of the field increases with energy (by a factor  $\sim 10$  between RHIC and the LHC), is reached very shortly ( $\ll 1$  fm/ $c$ ) after collision time [18], and decreases by several orders of magnitude by  $t = 1$  fm/ $c$  [21]. However, due to the formation of a QGP and to its finite electrical conductivity, large magnetic field values may be

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sustained along its entire lifetime. The production of a heavy quark pair also happens early in the collision history, within typical timescales of the order of  $t \sim 1/(2m_q) \sim 0.1$  fm/c [22], and with the subsequent evolution toward a bound state also occurring on a time range  $< 1$  fm/c [23,24], implying that polarization of charmonia may be influenced by the presence of the strong magnetic field generated in the collisions.

Another effect that may alter the polarization of quarkonia, via spin-orbit coupling, is the generation of a huge orbital angular momentum of the medium, again directed along the perpendicular to the reaction plane [25,26]. In the hydrodynamic description of the QGP, this amounts to the creation of a rotating fluid with a large vorticity, with estimated values up to  $\sim 10^{22}$  s $^{-1}$  [27], much larger than any other fluid existing in the Universe.

Measured effects that may be related to strong e.m. fields and/or vorticity include the polarization of  $\Lambda$  hyperons [27,28], discovered by STAR, and among vector mesons (spin quantum number equal to unity) a spin alignment of the  $\phi$  and  $K^{*0}$ , observed by the ALICE [29] and STAR [30] experiments. These hadrons are expected to be formed, up to a few GeV/c transverse momentum, by light and strange quarks produced in the QGP, via recombination processes occurring close in time to the hadronization transition. The charmonium vector mesons produced by regeneration effects, in particular, at low  $p_T$ , may therefore also exhibit spin-alignment effects as is the case for light vector mesons. These effects can be parametrized in terms of the  $\rho_{00}$  element of the spin-density matrix [31]. Because of angular momentum conservation, a net polarization of a particle sample induces an asymmetry in the angular distribution of the decay products. For the two-body dilepton decay of a vector meson, this distribution is given by

$$W(\theta) \propto \frac{1}{3 + \lambda_\theta} (1 + \lambda_\theta \cos^2 \theta), \quad (1)$$

where  $\theta$  is the polar emission angle of the positively charged decay lepton, with respect to a chosen axis [5]. It can be shown that  $\lambda_\theta \propto (1 - 3\rho_{00})/(1 + \rho_{00})$  [32], so that the finite spin-alignment condition  $\rho_{00} \neq 1/3$  is equivalent to the finite polarization condition  $\lambda_\theta \neq 0$ .

In this Letter, we report the first measurement of the  $J/\psi$  polarization with respect to an axis perpendicular to the event plane, an experimental estimator of the reaction plane, carried out by ALICE in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The results refer to inclusive  $J/\psi$ , i.e., both prompt (direct production and contribution from decays of higher-mass charmonium states) and nonprompt (from decays of hadrons containing a  $b$  quark), with the latter accounting for less than 15% in the covered  $p_T$  range [33]. The only previously published result on  $J/\psi$  polarization for this collision system was also obtained by ALICE [34], by measuring, via the decay  $J/\psi \rightarrow \mu^+ \mu^-$ ,

the  $J/\psi$  polarization in the helicity and Collins-Soper reference frames. These measurements showed deviations from  $\lambda_\theta = 0$  with a  $\sim 2.1\sigma$  maximum significance at low  $p_T$ , for both reference frames. In these two reference frames, the polarization was measured with respect to directions directly connected with the production process, i.e., the momentum direction of the  $J/\psi$  itself (helicity) or the direction of motion of the colliding hadrons (Collins-Soper). By measuring the polarization with respect to the estimated reaction plane of the nuclear collision, as done in this analysis, one rather selects a reference frame that should naturally be connected with the observation of polarization effects due to the presence of early electromagnetic fields and/or QGP vorticity.

The data analyzed in this Letter were collected by ALICE in 2015 and 2018, and the  $J/\psi$  decay to muon pairs was studied in the muon spectrometer, which covers the pseudorapidity region  $-4 < \eta < -2.5$ . This detector consists of a 3 Tm dipole magnet, a system of five tracking (cathode pad chambers) and two triggering stations (resistive plate chambers), and two hadron absorbers. It is described in detail in Refs. [35,36]. The other detectors used for this analysis are (i) the two layers of the silicon pixel detector, SPD ( $|\eta| < 2$  and  $|\eta| < 1.4$ ), which represent the innermost part of the ALICE central barrel and are used for the determination of the position of the primary interaction vertex and the estimate of the event plane of the collision and (ii) the two V0 scintillator arrays ( $-3.7 < \eta < -1.7$  and  $2.8 < \eta < 5.1$ ), which provide the minimum bias (MB) trigger, given by a coincidence of signals from their two sides, and are used for the rejection of beam-gas interactions. They are also used for the determination of the centrality of the collisions (see below) and for the estimate of the resolution of the event-plane determination.

The analyzed events were recorded using a dimuon trigger, defined as the coincidence of a MB trigger together with the detection of two opposite-sign candidate tracks in the triggering system of the muon spectrometer. The trigger algorithm applies a nonsharp  $p_T$  cut, which has 50% efficiency at 1 GeV/c and becomes fully efficient ( $> 98\%$ ) beyond  $p_T \sim 2$  GeV/c. Selection criteria were applied at the single muon and muon pair level (see Refs. [17,34,37] for details). Opposite-sign dimuons were selected in the rapidity interval  $2.5 < y < 4$  and invariant mass range  $2.1 < m_{\mu\mu} < 4.9$  GeV/c $^2$ . (Because of the symmetry of the collision system, a positive notation was adopted for rapidity.) The events were classified from central to peripheral according to the decreasing energy deposition in the V0 system, which is directly connected to the degree of geometric overlap of the colliding nuclei [38]. For the analysis, the most central 90% of the inelastic hadronic cross section was selected, which ensures full efficiency of the MB selection.

The event-plane angle was estimated, event per event, as the second harmonic symmetry plane of charged particles at midrapidity,  $\Psi_2 = \tan^{-1}(Q_{2,y}/Q_{2,x})/2$ , where the transverse components of the flow vector  $Q_2$  were obtained as  $Q_{2,x} = \sum_i \cos(2\varphi_i)$  and  $Q_{2,y} = \sum_i \sin(2\varphi_i)$ , with  $\varphi_i$  being the azimuthal angle, in the center-of-mass frame of the collision, of the  $i$ th tracklet defined by combinations of hits in the SPD. A recentering procedure [39] was performed, as a function of the longitudinal position of the primary vertex, to remove nonuniformities in the SPD acceptance.

Each dimuon was weighted by the inverse of the product of its acceptance times reconstruction efficiency ( $A \times \varepsilon$ ), assuming it comes from the decay of a  $J/\psi$ . A Monte Carlo simulation was used for the calculation of  $A \times \varepsilon$ , with the generated  $J/\psi$  signal being injected inside real MB events, to properly reproduce the effect of detector occupancy and its variation from one centrality class to another. The  $y$  and  $p_T$  input distributions for the  $J/\psi$  were taken from Ref. [17]. In addition, the  $J/\psi$  were generated as unpolarized, i.e., a flat distribution was assumed for the cosine of the polar angle ( $\theta$ ) distribution of their positive decay muons with respect to the perpendicular to the event plane. A significant  $p_T$  dependence of the shape of  $A \times \varepsilon$  as a function of  $\cos\theta$  was found, and for this reason the correction was performed on a fine 2D grid in  $\cos\theta$  vs  $p_T$ . Thanks to a narrow binning that leads to a small variation of these variables in each cell, the corresponding  $A \times \varepsilon$  values were found to be only minorly sensitive to variations in the input distributions. Typical values of  $A \times \varepsilon$  are  $\sim 10\%$  around  $\cos\theta = 0$ , increase by a factor 2–2.5 when  $|\cos\theta| = 1$ , and vary by  $\sim 15\%$  from peripheral to central events.

The extraction of the polarization parameter  $\lambda_\theta$  was carried out as a function of centrality, for the transverse momentum interval  $2 < p_T < 6$  GeV/ $c$ , and as a function of  $p_T$  for the centrality intervals 0%–20% (most central) and 30%–50%. For each range in centrality and  $p_T$  the  $A \times \varepsilon$ -corrected invariant mass distributions were separately obtained for ten  $\cos\theta$  intervals in  $-1 < \cos\theta < 1$ . The number of  $J/\psi$  for each interval was obtained by means of a  $\chi^2$  minimization fit, with the signal being described by a double-sided crystal ball function or a pseudo-Gaussian with a mass-dependent width [40]. The central value of the mass and the width of the  $J/\psi$  were kept as free parameters of the fit, while the non-Gaussian tail parameters were fixed to the Monte Carlo values. The small contribution from the  $\psi(2S)$  was included, but was found to have a negligible influence on the fit result. The background was empirically reproduced by a fourth-degree polynomial times an exponential, or a pseudo-Gaussian with a width quadratically dependent on the mass. The fits have  $\chi^2$  per degrees of freedom values ranging from 0.6 to 1.8. The minimum value of the signal over background ratio is 0.12 and the corresponding significance of the

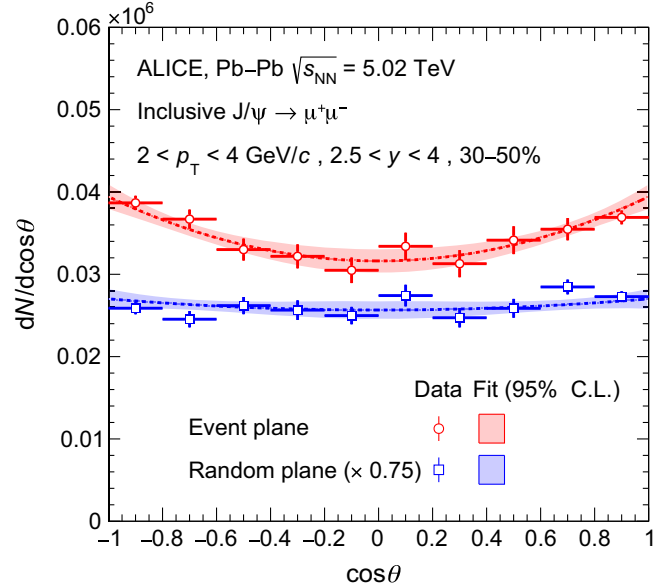


FIG. 1. Fit to the  $(A \times \varepsilon)$ -corrected angular distribution of the positive muons from the  $J/\psi$  decay, for the interval  $2 < p_T < 4$  GeV/ $c$  and the centrality range 30%–50% (red points and curve). Only statistical uncertainties are shown for the data points. The shaded area represents the uncertainty associated with the fit. Also shown (blue points and curve) is the result of a control analysis where, for each event, the estimated event plane was rotated by a random angle.

signal is 36, with an increase from central to peripheral collisions and from low to high  $p_T$ . Finally, the  $\lambda_\theta$  values were obtained by fitting the  $\cos\theta$  distributions, with  $\theta$  being the angle of the positive-sign decay muon with respect to the axis perpendicular to the event plane, according to Eq. (1). In Fig. 1, an example of a fit to  $A \times \varepsilon$ -corrected angular distributions is shown, together with the result of a similar analysis where for each event the event-plane angle was replaced by a randomly chosen direction. A flat angular distribution for the  $J/\psi$  was obtained in the latter case. For all the studied combinations of  $p_T$  and centrality intervals, the values of  $\lambda_\theta$  extracted with a random assignment of the event plane were compatible with zero, within at most  $1\sigma$ . Finally,  $\lambda_\theta$  must be corrected for the finite resolution on the event-plane determination. The procedure follows the one used for the  $K^{*0}$  and  $\phi$  mesons spin-alignment measurement [29] which was proposed in Ref. [41], where a simple relation between the true and observed values of the spin-density matrix element, involving the event-plane resolution, was given. The centrality-dependent resolution [42] has a maximum value around 0.8–0.9, decreasing for very central and peripheral events, and induces a modest effect (up to  $+0.02$ ) on  $\lambda_\theta$ .

The systematic uncertainties on  $\lambda_\theta$  are related to the extraction of the  $J/\psi$  signal, to the kinematic distributions used as inputs to the Monte Carlo simulation, and to the estimate of the dimuon trigger efficiency. The first source

TABLE I. Systematic uncertainties on the evaluation of the  $\lambda_\theta$  parameter. The quoted uncertainties for the various sources are considered as uncorrelated.

$p_T$ (GeV/c)	Centrality	Signal	Trigger	Input MC	Total
2–6	0%–20%	0.045	0.006	0.006	0.046
	20%–40%	0.027	0.010	0.006	0.030
	40%–60%	0.015	0.006	0.002	0.017
	60%–90%	0.016	0.007	0.003	0.018
Centrality	$p_T$ (GeV/c)	Signal	Trigger	Input MC	Total
0%–20%	2–4	0.063	0.017	0.007	0.065
	4–6	0.020	0.011	0.007	0.024
	6–10	0.024	0.006	0.008	0.026
30%–50%	2–4	0.032	0.007	0.006	0.033
	4–6	0.026	0.015	0.008	0.031
	6–10	0.025	0.006	0.012	0.029

was evaluated by comparing the  $\lambda_\theta$  values obtained from angular distributions extracted with different choices for the signal and background shapes in the invariant mass fits and by using various fit ranges, from  $2.1 < m_{\mu\mu} < 4.9$  GeV/ $c^2$  (wider) to  $2.5 < m_{\mu\mu} < 4.5$  GeV/ $c^2$  (narrower). The absolute values of this systematic uncertainty, taken as the rms of the  $\lambda_\theta$  values, range between 0.02 and 0.04 as a function of centrality and from 0.02 to 0.06 as a function of  $p_T$ . Concerning the Monte Carlo generation, due to suppression and regeneration effects on the  $J/\psi$  yields occurring in Pb-Pb collisions [17], the  $p_T$  and  $y$  distributions have a centrality dependence. A weight to the default centrality-integrated distributions was applied in order to reproduce such dependence in the  $A \times \varepsilon$  calculations. The effect on the evaluation of  $\lambda_\theta$  was found to be small, being less than 0.01 as a function of centrality, and smaller than 0.02 as a function of  $p_T$ . Since the muon trigger response function exhibits a slight difference in data and in the Monte Carlo (MC) for  $p_T < 2$  GeV/ $c$ , the  $\lambda_\theta$  parameter was extracted

after weighting the  $A \times \varepsilon$  in order to take into account this discrepancy. The variation of the results after this correction,  $\sim 0.01$  as a function of centrality and  $0.01$ – $0.02$  as a function of  $p_T$ , was taken as the systematic uncertainty on the trigger efficiency. Further efficiency-related uncertainties (tracking, matching between tracks in the tracking detectors and tracklets in the trigger detectors) were found to have a negligible influence on the polarization parameters. The total systematic uncertainty on  $\lambda_\theta$  was obtained as the quadratic sum of the values corresponding to each source, see Table I.

In Fig. 2, the centrality dependence of  $\lambda_\theta$  for the range  $2 < p_T < 6$  GeV/ $c$  is presented (left panel), as well as the  $p_T$  dependence of  $\lambda_\theta$  for central (0%–20%) and intermediate centrality (30%–50%) events (right panel). As a function of centrality, a small but significant transverse polarization is found from central collisions down to the 40%–60% centrality interval, where a  $3.5\sigma$  effect is observed. The results as a function of  $p_T$  may indicate that the deviation from zero is larger at small transverse momentum. The maximum deviation from  $\lambda_\theta = 0$  as a function of  $p_T$  is observed for  $2 < p_T < 4$  GeV/ $c$  and 30%–50% centrality where, considering the total uncertainty, a  $3.9\sigma$  effect is present. The results correspond to inclusive  $J/\psi$  production, implying that a small contribution from a potential polarization of parent beauty hadrons, which could anyway be diluted in the decay process [43], might be present.

Previous measurements carried out by ALICE on  $K^{*0}$  and  $\phi$  spin alignment [29] had established evidence of a significant effect for vector mesons in heavy-ion collisions, stronger at low  $p_T$  and for semicentral Pb-Pb collisions. The maximum  $\lambda_\theta$  value measured for the  $J/\psi$  ( $\sim 0.2$ ) in this analysis would translate, in the language of spin matrix elements, to  $\rho_{00} \sim 0.25$ . This result implies a deviation of  $-0.08$  from  $\rho_{00} = 1/3$  (corresponding to no spin alignment), in the same direction with respect to the corresponding deviations of about  $-0.2$  for  $K^{*0}$  and  $-0.1$  for  $\phi$ . It can

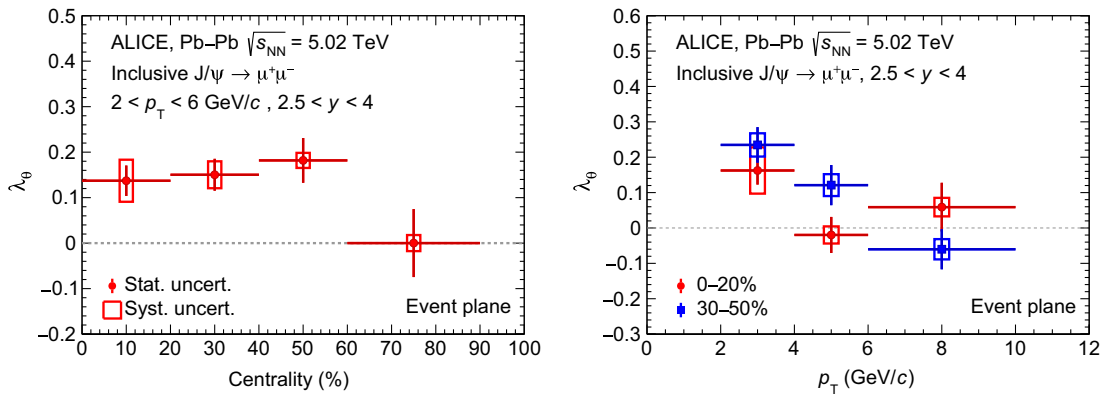


FIG. 2. Centrality (left) and  $p_T$  dependence (right) of  $\lambda_\theta$ . The vertical bars represent the statistical uncertainties, while the boxes correspond to the systematic uncertainties. The horizontal bars show the size of the corresponding centrality and  $p_T$  ranges, with the data points being located at the center of each interval.

be noted that the  $p_T$  and centrality dependence of the observed spin-alignment effects are qualitatively consistent between light vector mesons [29] and charmonia. In particular, for the centrality dependence, the possible increase of  $\lambda_\theta$  from central to semicentral collisions, followed by a decrease in peripheral events, is in qualitative agreement with the dependence of the initial angular momentum on impact parameter [26]. The results for  $K^{*0}$  and  $\phi$  are consistent with a scenario of quark polarization in the presence of a large angular momentum of the system [29]. The results shown in this Letter may confirm this interpretation also for the charmonium sector. On the other hand, charm quarks are produced early in the collision history and could be more sensitive to additional effects related to strong electromagnetic fields. Those effects would lead to a net increase of  $\rho_{00}$  with respect to  $1/3$  [44]. Our data, being roughly compatible with the result for  $K^{*0}$  and  $\phi$ , do not give evidence for a scenario that includes a significant additional contribution to  $\rho_{00}$ . Clearly, these hints need to be confirmed by theory studies devoted to charm and charmonium production, which are currently under development [45]. On the experimental side, significant detector upgrades and a factor  $\sim 20$  increase in the available integrated luminosity in the LHC runs 3 and 4 [46,47] will allow a decisive improvement in the statistical significance of these results as well as an extension toward midrapidity. Furthermore, a first measurement for  $\Upsilon$  states, which are produced even earlier in the collision history and experience little regeneration in the QGP, could be carried out. This measurement will potentially be more sensitive to the early strong electromagnetic fields.

In summary, we have reported on the first measurement of the polarization for inclusive  $J/\psi$  produced in Pb-Pb interactions at  $\sqrt{s_{NN}} = 5.02$  TeV, carried out by ALICE using the direction perpendicular to the event plane of the collision as the polarization axis. This choice makes this measurement potentially sensitive to the strong magnetic field created in high-energy nuclear collisions, as well as to vorticity effects in the QGP. A small but significant transverse polarization signal, reaching  $3.9\sigma$  for  $2 < p_T < 4$  GeV/ $c$  and 30%–50% centrality, is measured. The effect is roughly compatible with that seen for light vector mesons and does not show a significant additional contribution that may be related to the presence of a strong electromagnetic field. However, the differences in the production timescale of the involved quarks require dedicated theory studies for a quantitative understanding of this observation and a precise connection with the QGP properties at its origin.

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