J/ψ Polarization in pp Collisions at $\sqrt{s} = 7$ TeV

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The ALICE Collaboration has studied J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV at the LHC through its muon pair decay. The polar and azimuthal angle distributions of the decay muons were measured, and results on the J/ψ polarization parameters λ_θ and λ_ϕ were obtained. The study was performed in the kinematic region $2.5 < y < 4$, $2 < p_t < 8$ GeV/c, in the helicity and Collins-Soper reference frames. In both frames, the polarization parameters are compatible with zero, within uncertainties.

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Almost 40 years after its discovery, heavy quarkonium still represents a challenging testing ground for models [1] based on quantum chromodynamics (QCD). Results obtained for charmonium production at the Tevatron collider in the 1990s [2] led theory to recognize the role of intermediate quark-antiquark color-octet states in the production process, in the framework of the nonrelativistic QCD model [3]. This approach brought the calculations of p_t spectra to agree rather well with the data [4] (p_t is the transverse momentum, i.e., the momentum component perpendicular to the colliding beam direction). However, the same calculations were not able to reproduce satisfactorily the polarization results for the J/ψ obtained by the CDF experiment at $\sqrt{s} = 1.96$ TeV [5]. In particular, the nonrelativistic QCD model at leading order predicts for high-p_t J/ψ ($p_t \gg m_{J/\psi}$) a significant transverse polarization, i.e., a dominant angular momentum component $J_z = \pm 1$, the z axis being defined by the J/ψ's own momentum direction in the center of mass frame of the pp ($p\bar{p}$) collision. Contrary to this expectation, the CDF data [5] rather exhibit a mild longitudinal polarization ($J_z = 0$). In a recent renaissance of quarkonium studies, also related to the publication of results from the Relativistic Heavy Ion Collider at $\sqrt{s} = 0.2$ TeV [6], next-to-leading-order corrections for both color-singlet and color-octet intermediate states were calculated, and their impact on the p_t spectra was found to be quite important [7–9]. The influence of these corrections on the polarization calculations is expected to be significant [10,11] and still has not been completely worked out. The start-up of the LHC provides the possibility to perform charmonium measurements in a new energy domain, over large ranges in p_t and rapidity ($y = 0.5 \ln[(E + p_z)/(E - p_z)]$, where E is the energy and p_z is the momentum component parallel to the colliding beam direction). Various theoretical approaches [8,12,13] proved to be rather successful in describing the first LHC experimental results on the J/ψ p_t spectra [14–17]. The measurement of polarization clearly represents a more stringent test of the theoretical calculations, offering therefore the possibility of confirming or ruling out the current QCD approach to charmonium production.

In this Letter, we present the results of a study of J/ψ polarization at the LHC, carried out by the ALICE experiment in pp collisions at $\sqrt{s} = 7$ TeV. The ALICE experiment [18] is based on a central barrel, covering the pseudorapidity region $|\eta| < 0.9$ [19], and a muon spectrometer, with $2.5 < \eta < 4$ coverage. The polarization results presented in this Letter refer to inclusive J/ψ, measured via the $J/\psi \to \mu^+\mu^-$ decay in the muon spectrometer. The spectrometer [17] consists of a 10 interaction length (λ_I) thick front absorber, to remove hadrons, followed by a 3 T m dipole magnet. Charged particles which exit the front absorber are tracked in a detector system made up of five stations, each one with two planes of cathode pad chambers. The tracking system is followed by a $7.2\lambda_I$ iron wall, which absorbs secondary hadrons escaping the front absorber and low-momentum muons. Finally, a trigger system, based on resistive plate chambers, is used to select candidate muons with a transverse momentum larger than a given programmable threshold.

The analysis presented in this Letter was carried out on a significant fraction of the 2010 sample of muon-triggered events, corresponding to an integrated luminosity $L_{\rm int} \sim 100$ nb^{-1}. The usual event selection cuts, already applied to a previous analysis of J/ψ production [17], were also used for the polarization study. Events with at least one vertex reconstructed in the inner tracking system [20] are retained for the following analysis if they contain at least two tracks reconstructed in the muon spectrometer, out of which at least one has to satisfy the trigger condition (1 GeV/c p_t threshold). We note that with this requirement the acceptance of the spectrometer for J/ψ extends down to $p_t = 0$. The tracks must satisfy the condition $2.5 < \eta < 4$ and must also have $17.6 < R_{\rm abs} < 88.9$ cm,

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where $R_{\rm abs}$ is the radial distance of the track from the beam axis at the exit of the front absorber ($z = 503$ cm). The latter requirement eliminates forward tracks, which, due to the high-Z material used in the absorber in that region, are strongly affected by multiple scattering. Finally, a rapidity cut $2.5 < y < 4$ is applied to the selected muon pairs.

The distribution of the J/ψ decay products can be expressed in its general form [21] as

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

where θ (ϕ) are the polar (azimuthal) angles in a given reference frame. In this analysis, the Collins-Soper (CS) and helicity (HE) frames were considered. In the CS frame, the z axis is defined as the bisector of the angle between the direction of one beam and the opposite of the direction of the other one, in the rest frame of the decaying particle. In the HE reference frame, the z axis is given by the direction of the decaying particle in the center of mass frame of the collision. The $\phi = 0$ plane is the one containing the two beams, in the J/ψ rest frame. Equation (1) contains the three parameters λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$, which quantify the degree of polarization. In particular, $\lambda_\theta > 0$ values indicate transverse polarization, while a longitudinal polarization gives $\lambda_\theta < 0$. In principle, the values of the parameters could be extracted by means of a fit to the acceptance-corrected 2D distributions for $\cos\theta$ vs ϕ. However, the limited J/ψ statistics (about 6.8×10^3 signal events in the p_t range under study) makes a 2D binning impossible. Therefore the study of the angular distributions was separately performed on the polar and azimuthal variables. In particular, λ_θ and λ_ϕ were obtained by studying the distributions

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

obtained by integrating Eq. (1) in the ϕ and $\cos\theta$ variables, respectively.

The distributions of the angular variables for the J/ψ decay products were obtained starting from the study of the dimuon invariant mass spectra. The study was performed in five bins for the $|\cos\theta|$ variable (the angular distribution is symmetric with respect to $\cos\theta = 0$), in the range $0 < |\cos\theta| < 0.8$. For the azimuthal variable, four bins in $|\phi|$ were defined, in the range $0 < |\phi| < \pi/2$ (values between $\pi/2$ and π were mirrored around $|\phi| = \pi/2$, due to the period of the $\cos 2\phi$ function). The analysis was carried out in three transverse momentum intervals ($2 < p_t < 3$ GeV/c, $3 < p_t < 4$ GeV/c, and $4 < p_t < 8$ GeV/c). The limits of the explored p_t range are related to the strong decrease of the acceptance for large $|\cos\theta|$ values at low p_t and to the limited statistics at high p_t.

The number of J/ψ signal events for the various bins in $|\cos\theta|$ and $|\phi|$ were obtained by means of fits to the corresponding dimuon invariant mass spectra performed in the range $1.5 < m_{\mu\mu} < 5$ GeV/c^2, and in Fig. 1 we show one of them as an example. The J/ψ signal was described by a Crystal Ball (CB) function [22], while for the background an empirical function, corresponding to a Gaussian with a width linearly depending on mass, was adopted. The position of the CB peak was left as a free parameter in the fits and was found to correspond to the nominal J/ψ pole mass within at most 1%. The width of the CB function obtained from the data (between 72 and 120 MeV/c^2, depending on the kinematics) was found to be in agreement with the Monte Carlo (MC) within $\sim$8–10 MeV/c^2. In the fits, the width of the CB function for each bin i (where i represents a certain $|\cos\theta|$ or $|\phi|$ interval for the J/ψ p_t bin under study) was fixed to $\sigma^i_{J/\psi} = \sigma_{J/\psi}(\sigma^{i,\rm MC}_{J/\psi}/\sigma^{\rm MC}_{J/\psi})$, i.e., by scaling the measured width for the angle-integrated spectrum with the MC ratio between the widths for the bin i and for the integrated spectrum. The quality of all the fits is satisfactory, with χ^2/d.o.f. in a range between 0.63 and 1.34. Signal over background ratios in a $\pm 3\sigma$ mass window around the CB peak vary between 0.5 and 3.5. The number of signal events per bin ranges from $\sim$100 (for $2 < p_t < 3$ GeV/c, $0.6 < |\cos\theta_{\rm CS}| < 0.8$) to $\sim$1000 (for $2 < p_t < 3$ GeV/c, $0 < |\cos\theta_{\rm CS}| < 0.15$).

The polarization parameters for the J/ψ were obtained by correcting the number of signal events $N^i_{J/\psi}$ for each bin for the product $A_i\varepsilon_i$ of acceptance times detection efficiency, calculated via MC simulation, and then fitting the corrected angular distributions with the functions shown in Eq. (2). The simulation includes, for the tracking chambers, a map of dead channels and the residual misalignment of the detection elements and, for the trigger chambers, an evaluation of their efficiency based on data. It also includes a random misalignment of the tracking detector elements,

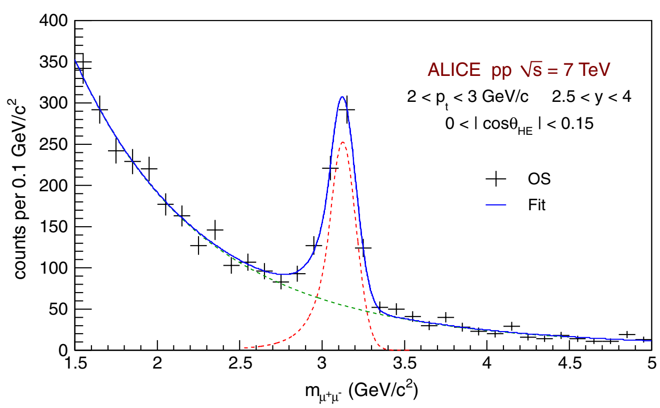

FIG. 1 (color online). The dimuon invariant mass spectrum for $2 < p_t < 3$ GeV/c, $0 < |\cos\theta_{\rm HE}| < 0.15$, together with the result of the fit. The contributions of the signal and background are also shown as dashed lines.

of the same size of the resolution obtained by the offline alignment procedure [17]. For both tracking and triggering detectors, the time variation of the efficiencies during the data-taking period was accounted for (see [17] for details). Since the $\cos\theta$ and ϕ acceptances are strongly correlated, the acceptance values as a function of one variable strongly depend on the input distribution used for the other variable. Given the fact that the correct input distributions are not known *a priori* but rather represent the outcome of the data analysis, an iterative procedure was followed in order to determine them. In the first iteration, a flat distribution of the angular variables (equivalent to a totally unpolarized J/ψ distribution) was adopted to calculate the acceptances. After correcting the signal with those acceptances, a first determination of the polarization parameters is performed, and the results are then used in a second determination of the acceptance values. The procedure is then repeated until convergence is reached; i.e., the extracted polarization parameters do not vary by more than 0.005 between two successive iterations. This occurs, for this analysis, after at most three steps. It was also checked that by using polarized MC input distributions in the first iteration the procedure converges towards the same results as in the default, unpolarized, case. Typical $A_i\varepsilon_i$ values vary between $\sim$0.22 (0.05) at low p_t and large $|\cos\theta|$ and $\sim$0.41 (0.63) at large p_t and small $|\cos\theta|$ for the HE (CS) frame.

A simultaneous study of the J/ψ polarization variables in several reference frames, as first carried out in hadroproduction studies by the HERA-*B* experiment [23], is particularly interesting since consistency checks on the results can be performed, using combinations of the polarization parameters which are frame-invariant. In particular we made use of the invariant $F = (\lambda_\theta + 3\lambda_\phi)/(1 - \lambda_\phi)$ [21], performing a simultaneous fit of the $|\cos\theta|$ and $|\phi|$ distributions in the two reference systems and further constraining the fit by imposing F to be the same in the CS and HE frames. In Fig. 2 we present, as an example, the result of such a fit relative to the last iteration of the $A_i\varepsilon_i$ calculation, for $2 < p_t < 3$ GeV/c. The χ^2/d.o.f. values (d.o.f. $= 10$) are 1.08, 1.00, 1.32 for $2 < p_t < 3$, $3 < p_t < 4$ and $4 < p_t < 8$ GeV/c, respectively, showing that the quality of the fits is good. Compatible results are obtained when the constraint on F is released.

In the analysis described so far, the $\lambda_{\theta\phi}$ parameter was implicitly assumed to be zero in the iterative acceptance calculation. In the one-dimensional approach followed in this analysis, $\lambda_{\theta\phi}$ could be estimated from the data, defining an *ad hoc* variable $\tilde{\phi}$, which is a function of $\cos\theta$ and ϕ and contains $\lambda_{\theta\phi}$ as a parameter (see [21] for details). In principle, the iterative procedure applied to λ_θ and λ_ϕ determination could be extended to include $\lambda_{\theta\phi}$; however, in some cases, relatively small statistical fluctuations in the distributions of the measured variables tend to induce large variations of the fitted values in the following iterations, leading to convergence problems. A check of the $\lambda_{\theta\phi} = 0$ assumption was done *a posteriori* for each p_t bin, by fitting the $\tilde{\phi}$ distributions, corrected with an acceptance which makes use of the measured λ_θ and λ_ϕ values as inputs. In this way, we get for all the p_t bins $\lambda_{\theta\phi}$ values compatible with zero for both CS and HE reference frames. We also note that all the previous experiments assumed $\lambda_{\theta\phi} = 0$ in their analysis, with the exception of HERA-B [23], who measured it in pA collisions at $\sqrt{s} = 41.6$ GeV and found values ranging from 0 to 0.05.

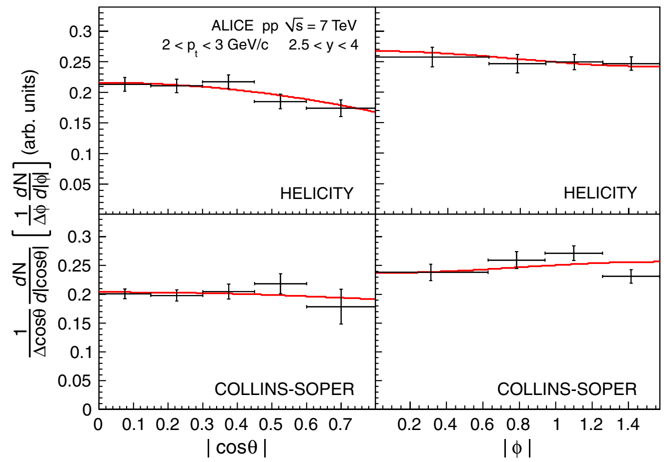

FIG. 2 (color online). The acceptance-corrected angular distributions for the J/ψ decay muons, for $2 < p_t < 3$ GeV/c. The simultaneous fit to the results in the CS and HE frames is also shown. The plotted errors are purely statistical. The horizontal bars represent the bin width.

Various sources of systematic uncertainty on the measurement of the polarization parameters have been investigated. The uncertainty on the signal extraction was studied by leaving in the fits the width of the CB function as a free parameter. This choice leads to an absolute variation of the polarization parameters between 0.02 and 0.10. Another sizable source of systematic uncertainty is the choice of the input distributions for p_t and y in the simulation. It was evaluated by comparing the results obtained with a parameterization of our 7 TeV results on differential J/ψ cross sections [17] with those obtained by using an extrapolation of lower energy results [24]. The absolute effect on the polarization parameters varies between 0.01 and 0.07. For the lowest p_t bin, the acceptance in the HE frame drops by about 40% in the highest $|\cos\theta|$ bin used in the analysis ($0.6 < |\cos\theta| < 0.8$) and has also a strong variation inside the bin itself. We therefore followed an alternative approach, fitting the angular spectrum in the restricted interval $0 < |\cos\theta| < 0.6$ (instead of the default choice $0 < |\cos\theta| < 0.8$), and we conservatively considered the variation in the result of the fit (0.15) as an additional systematic uncertainty on λ_θ. For consistency, the same evaluation was performed in the CS frame. The role of the systematic uncertainties on the trigger and tracking efficiency [17] was also studied. The first was evaluated by varying the efficiency values for each detector element by 2% with respect to the default values in the simulation. This choice is related to the estimated uncertainty on the detector efficiency calculation. For the second, we have used the rather conservative choice of comparing the reference results, obtained with realistic dead channel maps, with those relative to an ideal detector setup. The result is typically 0.03–0.04. Finally, by quadratically combining the results for the various sources, values between 0.04 and 0.21 are obtained for the global systematic uncertainties.

In Fig. 3, we show the results on λ_θ and λ_ϕ for inclusive J/ψ production. In both frames, all the parameters are compatible with zero, with a possible hint for a longitudinal polarization at low p_t (at a 1.6σ level) in the HE frame. The numerical values are given in Table I.

The inclusive J/ψ yield is composed of a "prompt" component [direct J/ψ + decay of the $\psi(2S)$ and χ_c resonances] and of a component from B-meson decays. In the p_t range accessed in this analysis, the B-meson decay component accounts for 10% ($2 < p_T < 3$ GeV/c), 12% ($3 < p_T < 4$ GeV/c), and 15% ($4 < p_T < 8$ GeV/c) of the inclusive yield, according to the LHCb measurements carried out in our same kinematical domain [15]. The polarization of the nonprompt component is expected to be quite small. In fact, even if a sizable polarization were observed when the polarization axis refers to the B-meson direction [25], it would be strongly smeared when it is calculated with respect to the direction of the decay J/ψ [15], as observed by CDF, who measured in this way $\lambda_\theta(J/\psi \leftarrow B) \sim -0.1$ in the HE frame [5]. By assuming

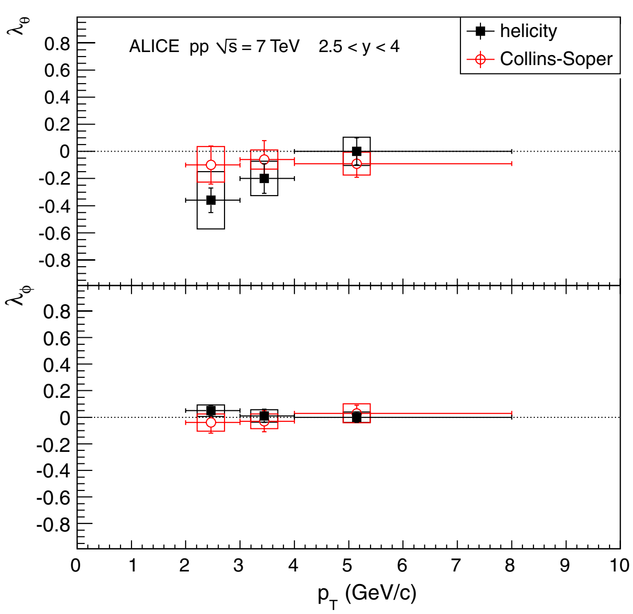

FIG. 3 (color online). λ_θ and λ_ϕ as a function of p_t for inclusive J/ψ, measured in the HE (closed squares) and CS (open circles) frames. The error bars represent statistical errors, while systematic uncertainties are shown as boxes.

conservatively $|\lambda_\theta(J/\psi \leftarrow B)| < 0.2$ for both frames, and taking into account the fraction of the inclusive yield coming from B-meson decays [15], the difference between prompt and inclusive J/ψ polarization was estimated and found to be at most 0.05, a value smaller than the systematic uncertainties of our measurements. Concerning higher-mass charmonia, the $\chi_c \to J/\psi + \gamma$ decay cannot be reconstructed in the muon spectrometer, and the $\psi(2S) \to \mu\mu$ statistics is currently too low. Values of the feed-down ratios measured mainly by lower energy experiments range from ~10% for the $\psi(2S)$ [26] to 25%–30% for the χ_c [27], implying that there could be a sizable difference between direct and prompt J/ψ polarization.

The results presented in Fig. 3 extend the study of the J/ψ polarization to LHC energies and therefore open up a new testing ground for theoretical models. At present, next-to-leading-order calculations for direct J/ψ polarization at the LHC via the color-singlet channel [10,12] predict a large longitudinal polarization in the HE frame ($\lambda_\theta \sim -0.6$) at $p_t \sim 5$ GeV/c, which is in contrast with the vanishing polarization that we observe in such a transverse momentum region. The contribution of the S-wave color-octet channels was also worked out [9] and indicates a significantly different trend (large transverse polarization) with respect to the color-singlet contribution, but again in contrast with our result. In this situation, a rigorous treatment on the theory side of all the color-octet terms (including P-wave contributions) is mandatory, as well as a study of the contribution of χ_c and $\psi(2S)$ feed-down which, as outlined before, is important for a quantitative comparison with our result [28]. Such studies are presently in progress, and the comparison of their outcome with the results presented in this Letter will allow a very significant test of the understanding of the heavy-quarkonium production mechanisms in QCD-based models.

In summary, we have measured the polarization parameters λ_θ and λ_ϕ for inclusive J/ψ production in $\sqrt{s} =$ 7 TeV pp collisions at the LHC. The measurement was carried out in the kinematical region $2.5 < y < 4$, $2 < p_t < 8$ GeV/c. The polarization parameters λ_θ and λ_ϕ are consistent with zero, in both the helicity and Collins-Soper reference frames. These results can be used as a stringent constraint on the commonly adopted QCD framework for heavy-quarkonium production.

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TABLE I. The values of λ_θ and λ_ϕ in the two reference frames. Statistical and systematic uncertainties are quoted separately.

	p_t ($\langle p_t \rangle$) (GeV/c)	λ_θ	λ_ϕ
HE	2–3 (2.5)	$-0.36 \pm 0.09 \pm 0.21$	$0.05 \pm 0.04 \pm 0.04$
	3–4 (3.4)	$-0.20 \pm 0.11 \pm 0.13$	$0.01 \pm 0.05 \pm 0.05$
	4–8 (5.1)	$0.00 \pm 0.10 \pm 0.10$	$0.00 \pm 0.04 \pm 0.04$
CS	2–3 (2.5)	$-0.10 \pm 0.14 \pm 0.13$	$-0.04 \pm 0.08 \pm 0.07$
	3–4 (3.4)	$-0.06 \pm 0.14 \pm 0.07$	$-0.03 \pm 0.08 \pm 0.05$
	4–8 (5.1)	$-0.09 \pm 0.10 \pm 0.08$	$0.03 \pm 0.06 \pm 0.07$

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