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Measurement of the prompt J/ψ and $\psi(2S)$ polarizations in pp collisions at $\sqrt{s} = 7$ TeV ☆

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ABSTRACT

The polarizations of prompt J/ψ and $\psi(2S)$ mesons are measured in proton–proton collisions at $\sqrt{s} =$ 7 TeV, using a dimuon data sample collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 4.9 fb^{-1}. The prompt J/ψ and $\psi(2S)$ polarization parameters λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$, as well as the frame-invariant quantity $\tilde{\lambda}$, are measured from the dimuon decay angular distributions in three different polarization frames. The J/ψ results are obtained in the transverse momentum range $14 < p_T < 70$ GeV, in the rapidity intervals $|y| < 0.6$ and $0.6 < |y| < 1.2$. The corresponding $\psi(2S)$ results cover $14 < p_T < 50$ GeV and include a third rapidity bin, $1.2 < |y| < 1.5$. No evidence of large polarizations is seen in these kinematic regions, which extend much beyond those previously explored.

1. Introduction

After considerable experimental and theoretical efforts over the past decades, the understanding of quarkonium production in hadron collisions is still not fully settled [1]. In particular, the polarization of J/ψ mesons is not satisfactorily described in the context of nonrelativistic quantum chromodynamics (NRQCD) [2], where the purely perturbative color-singlet production [3] is complemented by processes including possible nonperturbative transitions from colored quark pairs to the observable bound states. The S-wave quarkonia directly produced at high transverse momentum, p_T, are predicted to be transversely polarized [4–6] with respect to the direction of their own momentum. Contrary to this expectation, the CDF Collaboration measured a small longitudinal polarization in prompt J/ψ production [7]. Since the measurement includes both directly produced J/ψ mesons and those resulting from feed-down decays of heavier charmonia, the comparison between the theoretical predictions and the experimental results remained ambiguous [8]. Also the apparent lack of kinematic continuity between the fixed-target and the collider quarkonium polarization data [9] raises doubts on the reliability of these complex measurements. Given the absence of feed-down decays from heavier charmonia affecting $\psi(2S)$ production, the measurements of the $\psi(2S)$ polarization should be particularly informative, especially if made with higher accuracy and extending up to higher p_T than those provided by CDF [7].

The polarization of the $J^{PC} = 1^{--}$ quarkonium states can be measured through the study of the angular distribution of the leptons produced in their $\mu^+\mu^-$ decay [8],

$$W(\cos\vartheta, \varphi|\vec{\lambda}) = \frac{3}{4\pi(3+\lambda_\vartheta)}\big(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi\big), \quad (1)$$

where ϑ and φ are the polar and azimuthal angles, respectively, of the μ^+ with respect to the z axis of the chosen polarization frame. Robust quarkonium polarization measurements require extracting all the angular distribution parameters, $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$, in at least two polarization frames, as well as a frame-invariant polarization parameter, $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$ [10–12]. This approach was followed in the Υ polarization analysis of CDF [13], in recent theoretical calculations [14], in the detailed study of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ polarizations performed by CMS [15], and in the recent measurements of the J/ψ polarization at forward rapidity reported by ALICE [16] and LHCb [17]. This Letter presents the analogous measurement of the polarizations of the J/ψ and $\psi(2S)$ mesons (abbreviated as $\psi(nS)$, with $n = 1, 2$) promptly produced in pp collisions at a centre-of-mass energy of 7 TeV, at the LHC. The analysis is based on a dimuon sample collected in 2011, corresponding to an integrated luminosity of 4.9 fb^{-1}. The J/ψ ($\psi(2S)$) $\vec{\lambda}$ parameters are determined in several p_T bins in the range 14–70 GeV (14–50 GeV) and in two (three) absolute rapidity bins. Such a double-differential analysis is important to avoid

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obtaining diluted results from integrating over events characterized by significantly different kinematics [8].

The results correspond to the polarizations of the prompt $\psi(n\mathrm{S})$ states. The nonprompt component, mostly from decays of B mesons, is explicitly removed by using a proper-lifetime measurement. A significant fraction of the J/ψ prompt cross section is caused by feed-down decays from the $\psi(2\mathrm{S})$ (more than 8%, increasing with p_T) and from the χ_c (more than 25%) [18]. There are no feed-down decays from heavier charmonium states to the $\psi(2\mathrm{S})$ state, making it particularly interesting and easier to compare the measured polarization of this state with theoretical calculations. The polarization extraction method uses the dimuon invariant-mass distribution to separate the $\psi(n\mathrm{S})$ signal contributions from the continuum muon pairs from other processes (mostly pairs of muons resulting from decays of uncorrelated heavy-flavor mesons).

The two-dimensional shape of the decay angular distribution (in $\cos\vartheta$ and φ) is used to extract the three frame-dependent anisotropy parameters in three polarization frames, characterized by different choices of the quantization axis in the production plane: the centre-of-mass helicity (HX) frame, where the z axis coincides with the direction of the $\psi(n\mathrm{S})$ momentum in the laboratory; the Collins–Soper (CS) frame [19], whose z axis is the bisector of the two beam directions in the $\psi(n\mathrm{S})$ rest frame; and the perpendicular helicity (PX) frame [20], with the z axis orthogonal to that in the CS frame. The y axis is taken, in all cases, to be in the direction of the vector product of the two beam directions in the charmonium rest frame, $\vec{P}_1 \times \vec{P}_2$ and $\vec{P}_2 \times \vec{P}_1$ for positive and negative dimuon rapidities, respectively. More details regarding these frames are provided in Ref. [8]. The parameter $\tilde{\lambda}$, introduced in Ref. [11] to provide an alternative and frame-independent characterization of the quarkonium polarization properties, is measured simultaneously with the other parameters. This multidimensional approach reduces and keeps under control the smearing effects of the (unavoidable) partial averaging of the results over the range of the production and decay kinematics. This is important to minimize the possible interpretation ambiguities in the comparison with theoretical predictions and other experimental measurements [8].

2. CMS detector and data processing

The CMS apparatus [21] was designed around a central element: a superconducting solenoid of 6 m internal diameter, providing a 3.8 T field. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke outside the solenoid and made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. The main subdetectors used in this analysis are the silicon tracker and the muon system, which enable the measurement of muon momenta over the pseudorapidity range $|\eta| < 2.4$.

The events were collected using a two-level trigger system. The first level consists of custom hardware processors and uses information from the muon system to select events with two muons. The "high-level trigger" significantly reduces the number of events written to permanent storage by requiring an opposite-sign muon pair that fulfills certain kinematic conditions: invariant mass $2.8 < M < 3.35$ GeV, $p_\mathrm{T} > 9.9$ GeV, and $|y| < 1.25$ for the J/ψ trigger; $3.35 < M < 4.05$ GeV and $p_\mathrm{T} > 6.9$ GeV for the $\psi(2\mathrm{S})$ trigger. There is no rapidity requirement on the $\psi(2\mathrm{S})$ trigger, given its lower cross section, permitting an extra bin at forward rapidity with respect to the J/ψ case. No p_T requirement is imposed on the single muons at trigger level, only on the dimuon. Both triggers require a dimuon vertex-fit χ^2 probability greater than 0.5%. Events where the two muons bend towards each other in the magnetic field are rejected to lower the trigger rate while retaining the events where the dimuon detection efficiencies are most reliable.

The dimuons are reconstructed by combining two opposite-sign muons. The muon tracks are required to have hits in at least 11 tracker layers, at least two of which should be in the silicon pixel detector, and to be matched with at least one segment in the muon system. They must have a good track-fit quality (χ^2 per degree of freedom smaller than 1.8) and point to the interaction region. The selected muons must also be close, in pseudorapidity and azimuthal angle, to the muon objects responsible for triggering the event. In order to ensure accurately measured muon detection efficiencies, the analysis is restricted to muons produced within the range $|\eta| < 1.6$ and having transverse momentum above 4.5, 3.5, and 3.0 GeV for $|\eta| < 1.2$, $1.2 < |\eta| < 1.4$, and $1.4 < |\eta| < 1.6$, respectively. The continuum background due to pairs of uncorrelated muons is reduced by requiring a dimuon vertex-fit χ^2 probability larger than 1%. After applying all event selection criteria and background removal, the total numbers of prompt plus nonprompt J/ψ events are 2.3 M and 2.4 M in the rapidity bins $|y| < 0.6$ and $0.6 < |y| < 1.2$, respectively. The corresponding $\psi(2\mathrm{S})$ yields are 126 k, 136 k, and 55 k for $|y| < 0.6$, $0.6 < |y| < 1.2$, and $1.2 < |y| < 1.5$, respectively. In each of these $|y|$ ranges, the analysis is performed in several p_T bins, with boundaries at 14, 16, 18, 20, 22, 25, 30, 35, 40, 50, and 70 GeV for the J/ψ, and 14, 18, 22, 30, and 50 GeV for the $\psi(2\mathrm{S})$.

The single-muon detection efficiencies are measured by a tag-and-probe technique [22], using event samples collected with dedicated triggers enriched in dimuons from J/ψ decays, where a muon is combined with a track and the pair is required to have an invariant mass within the range 2.8–3.4 GeV. The measurement procedure has been validated in the fiducial region of the analysis with detailed Monte Carlo (MC) simulation studies. The single-muon efficiencies are precisely measured and parametrized as a function of p_T, in eight $|\eta|$ bins, to avoid biases in the angular distributions that could mimic polarization effects. Their uncertainties, reflecting the statistical precision of the tag-and-probe samples and possible imperfections of the parametrization, contribute to the systematic uncertainty in the polarization measurement. At high dimuon p_T, when the two decay muons might be emitted relatively close to each other, the dimuon trigger has a lower efficiency than the simple product of the two single-muon efficiencies. Detailed MC simulations, validated with data collected with single-muon and dimuon triggers, are used to correct these trigger-induced muon-pair correlations.

3. Extraction of the polarization parameters

For each $\psi(n\mathrm{S})$ $(p_\mathrm{T}, |y|)$ bin, the dimuon invariant-mass distribution is fitted, using an unbinned maximum-likelihood fit, with an exponential function representing the underlying continuum background and two Crystal Ball (CB) functions [23] representing each peak. The two CB functions have independent widths, σ_{CB_1} and σ_{CB_2}, to accommodate the changing dimuon invariant-mass resolution within the rapidity cells, but share the same mean μ_CB and tail factors α_CB and n_CB (the latter fixed to 2.5).

Fig. 1 shows two representative dimuon invariant-mass distributions in specific kinematic bins of the analysis. The dimuon invariant-mass resolution σ at the $\psi(n\mathrm{S})$ masses is evaluated from the fitted signal shapes, as $\sqrt{f_{\mathrm{CB}_1}\sigma^2_{\mathrm{CB}_1} + (1 - f_{\mathrm{CB}_1})\sigma^2_{\mathrm{CB}_2}}$, where f_{CB_1} is the relative weight of the CB_1 function. The p_T-integrated values

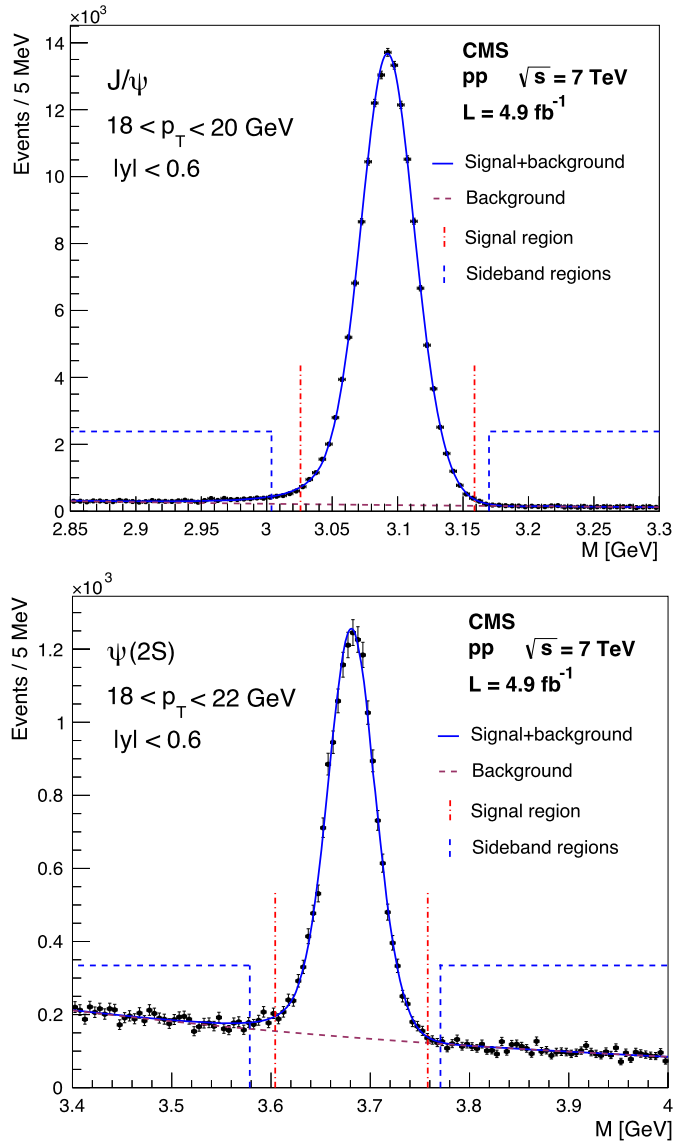

Fig. 1. Dimuon invariant-mass distribution in the J/ψ (top) and $\psi(2S)$ (bottom) regions for an intermediate p_T bin and $|y| < 0.6$. The vertical lines delimit the signal region (dot-dashed) and the mass sidebands (dashed). The results of the fits are shown by the solid (signal + background) and dashed (background only) curves.

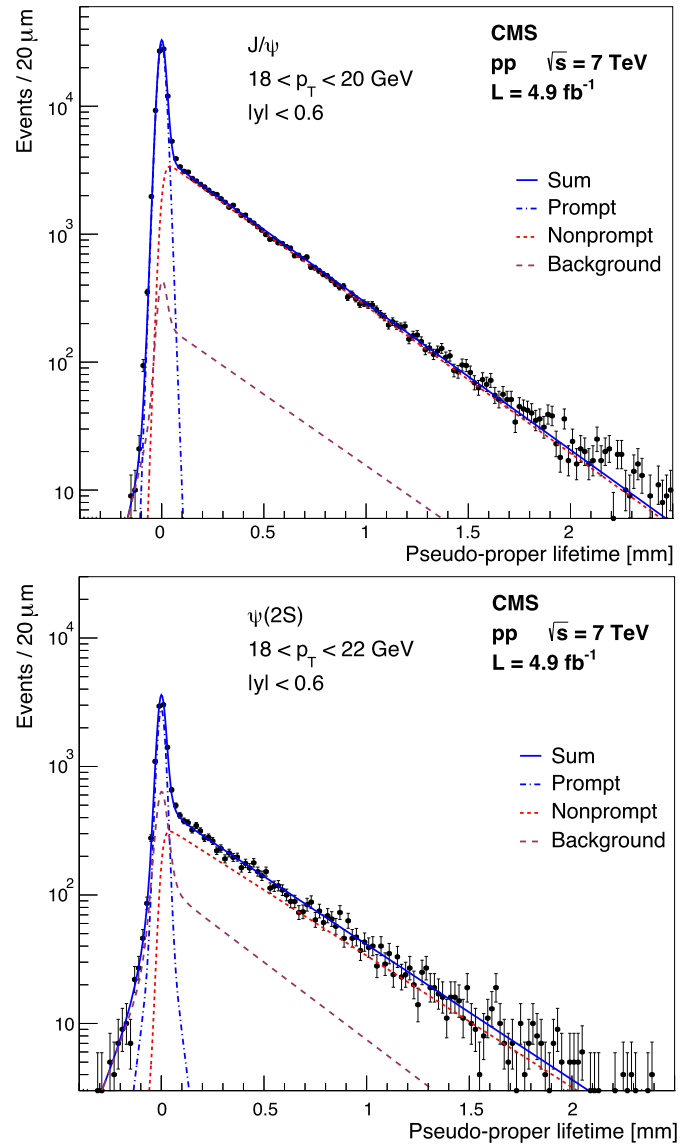

Fig. 2. Pseudo-proper-lifetime distribution in the J/ψ (top) and $\psi(2S)$ (bottom) mass regions for intermediate p_T bins and $|y| < 0.6$. The results of the fits are shown by the solid curve, representing the sum of three contributions: prompt (dash-dotted), nonprompt (dotted), and background (dashed).

are $\sigma_{J/\psi} = 21$ and 32 MeV for $|y| < 0.6$ and $0.6 < |y| < 1.2$, respectively, and $\sigma_{\psi(2S)} = 25$, 37, and 48 MeV for $|y| < 0.6$, $0.6 < |y| < 1.2$, and $1.2 < |y| < 1.5$, respectively. For each $(p_T, |y|)$ bin, the measured mass resolution is used to define a $\pm 3\sigma$ signal window around the resonance mass [24], m, as well as two mass sidebands, at lower and higher masses: from 2.85 GeV to $m_{J/\psi} - 4\sigma_{J/\psi}$ and from $m_{J/\psi} + 3.5\sigma_{J/\psi}$ to 3.3 GeV for the J/ψ; from 3.4 GeV to $m_{\psi(2S)} - 4\sigma_{\psi(2S)}$ and from $m_{\psi(2S)} + 3.5\sigma_{\psi(2S)}$ to 4 GeV for the $\psi(2S)$. The larger gap in the low-mass sideband definition compared to the high-mass sideband minimizes the signal contamination induced by the low-mass tail of the signal peaks. The result of the invariant-mass fit provides the fraction of continuum-background events.

To minimize the fraction of charmonia from B decays in the sample used for the polarization measurement, a "prompt-signal region" is defined using the dimuon pseudo-proper lifetime [25], $\ell = L_{xy} \cdot m_{\psi(nS)}/p_T$, where L_{xy} is the transverse decay length in the laboratory frame. The measurement of L_{xy} is performed after removing the two muon tracks from the calculation of the primary vertex position; in the case of events with multiple collision vertices (pileup), we select the one closest to the direction of the dimuon momentum, extrapolated towards the beam line.

The modeling of the resolution of the pseudo-proper lifetime exploits the per-event uncertainty information provided by the vertex reconstruction algorithm. The prompt-signal component is modeled by the resolution function, the nonprompt component by an exponential decay function convolved with the resolution function, and the continuum-background component by the sum of three exponential functions, also convolved with the resolution function. This composite model describes the data well with a relatively small number of free parameters. The systematic uncertainties induced by the lifetime fit in the polarization measurement are negligible. Fig. 2 shows representative pseudo-proper-lifetime distributions for dimuons in the two $\psi(nS)$ signal regions, together with the results of unbinned maximum-likelihood fits, performed simultaneously in the signal region and mass sidebands.

The prompt-signal regions, dominated by prompt charmonium events, are defined as $\pm 3\sigma_\ell$ signal windows around $\ell = 0$, where

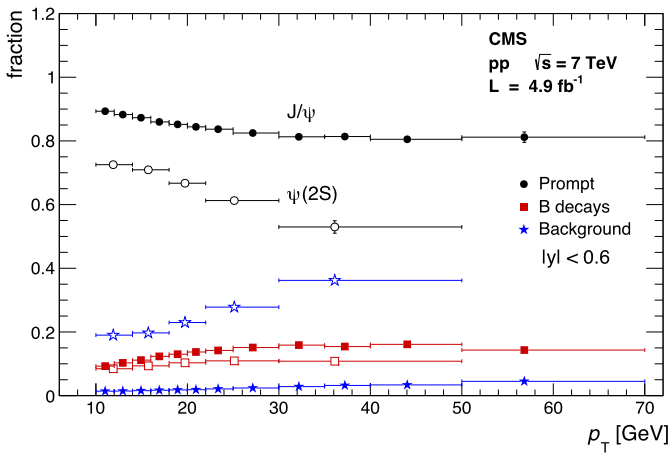

Fig. 3. Fractions of prompt charmonium (circles), charmonium from B decays (squares), and continuum-background (stars) events in the prompt-signal mass-lifetime J/ψ (closed symbols) and $\psi(2S)$ (open symbols) regions versus the dimuon p_T for $|y| < 0.6$. A sideband subtraction technique removes the B and continuum backgrounds from the polarization analysis.

the lifetime resolution, σ_ℓ, is measured to be (for the phase space probed in this analysis) in the range 12–25 μm, improving with increasing dimuon p_T. The fractions of charmonia from B decays (f_{NP}) and continuum-background events (f_B) included in these regions are shown in Fig. 3 versus the dimuon p_T, for $|y| < 0.6$.

For each $\psi(nS)$ state, the angular distribution of the continuum background is modeled as the weighted sum of the distributions measured in the two mass sidebands (restricted to the prompt-lifetime region), with weights derived under the assumption that the background distribution changes linearly with the dimuon mass. This assumption is validated by comparing the (small) differences of the effective background polarizations measured in the four dimuon invariant-mass sidebands. The angular distribution of the $\psi(nS)$ from B decays is modeled using the events in the $\psi(nS)$ mass peak belonging to the "nonprompt-lifetime region", $\ell > 3\sigma_\ell$, after subtracting the corresponding continuum-background contribution, interpolated from the nonprompt mass-sideband regions. As a cross-check of the analysis, the polarization of the nonprompt component was also measured, in two lifetime regions ($\ell > 3\sigma_\ell$ and $\ell > 5\sigma_\ell$), with consistent results.

The total background is the sum of the continuum-background and charmonia from B decays present in the prompt-signal region. To remove the background component, a fraction $f_{B,tot} = f_B + f_{NP}$ of the events is randomly selected by a procedure based on the likelihood-ratio L_B/L_{S+B}, where L_B (L_{S+B}) is the likelihood for an event under the background-only (signal-plus-background) hypothesis. This selection operates in such a way that the chosen events are distributed according to the $(p_T, |y|, M, \cos\vartheta, \varphi)$ distribution of the background model. The randomly selected events are removed from the sample.

The remaining (signal-like) events are used to calculate the posterior probability density (PPD) of the prompt-$\psi(nS)$ polarization parameters ($\vec{\lambda}$) for each kinematic bin,

$$\mathcal{P}(\vec{\lambda}) = \prod_i \mathcal{E}\left(\vec{p}_1^{\,(i)}, \vec{p}_2^{\,(i)}\right), \tag{2}$$

where $\mathcal{E}$ is the probability density as a function of the two muon momenta $\vec{p}_{1,2}$ in event i. Uniform priors are used in the full $\vec{\lambda}$ parameter space. Many previous polarization measurements were dependent on assumptions made about the production kinematics because of the use of simulated acceptance and efficiency dilepton $(\cos\vartheta, \varphi)$ maps, averaged over all events in the considered kinematic cell. This analysis, instead, uses the efficiencies measured as a function of muon momentum, attributing to each event a probability dependent on the full event kinematics (not only on $\cos\vartheta$ and φ) and on the values of the polarization parameters. The event probability is calculated as

$$\mathcal{E}(\vec{p}_1, \vec{p}_2) = \frac{1}{\mathcal{N}(\vec{\lambda})} W(\cos\vartheta, \varphi|\vec{\lambda})\, \epsilon(\vec{p}_1, \vec{p}_2), \tag{3}$$

where W is defined in Eq. (1) and $\epsilon(\vec{p}_1, \vec{p}_2)$ is the dimuon detection efficiency. The $\mathcal{N}(\vec{\lambda})$ normalization factor is obtained from integrating $W\epsilon$ over $\cos\vartheta$ and φ,

$$\begin{aligned}\mathcal{N} = \frac{1}{(3+\lambda_\vartheta)}\Bigg[&\left(\iint \epsilon(\vec{p}_1, \vec{p}_2)\, \mathrm{d}\cos\vartheta\, \mathrm{d}\varphi\right)\\ &+ \lambda_\vartheta \left(\iint \cos^2\vartheta\, \epsilon(\vec{p}_1, \vec{p}_2)\, \mathrm{d}\cos\vartheta\, \mathrm{d}\varphi\right)\\ &+ \lambda_\varphi \left(\iint \sin^2\vartheta \cos 2\varphi\, \epsilon(\vec{p}_1, \vec{p}_2)\, \mathrm{d}\cos\vartheta\, \mathrm{d}\varphi\right)\\ &+ \lambda_{\vartheta\varphi} \left(\iint \sin 2\vartheta \cos\varphi\, \epsilon(\vec{p}_1, \vec{p}_2)\, \mathrm{d}\cos\vartheta\, \mathrm{d}\varphi\right)\Bigg].\end{aligned} \tag{4}$$

To perform this integration, $\epsilon(\vec{p}_1, \vec{p}_2)$ is expressed in terms of $\cos\vartheta$ and φ using the background-removed $(p_T, |y|, M)$ distributions. The background-removal procedure is repeated 50 times to minimize the statistical fluctuations associated with its random nature, and the PPD is obtained as the average of the 50 individual densities. The value 50 is very conservative; 20 iterations would have been sufficient to provide stable results.

Fig. 4 illustrates the measured $\cos\vartheta$ and φ distributions in the HX frame for the case of J/ψ signal events in the kinematic bin $|y| < 0.6$ and $18 < p_T < 20$ GeV, after background removal. The data points are compared to curves reflecting the "best fit" (solid lines) as well as two extreme scenarios (dashed and dotted lines), corresponding to the λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$ values reported in the legends of the plots.

Most of the systematic uncertainties we have considered were studied and quantified (for each charmonium and each kinematic bin) with pseudo-experiments based on simulated events. Each test evaluates a specific systematic uncertainty and uses 50 statistically independent event samples, individually generated and reconstructed. The difference between the median of the 50 obtained polarization parameters and the injected values provides the systematic uncertainty corresponding to the effect under study. In particular, several signal and background polarization scenarios have been used to evaluate the reliability of the analysis framework, including extreme signal polarizations in the highest-p_T bins of the analysis, where the dimuon trigger inefficiency has the strongest effect. Possible residual biases in the muon or dimuon efficiencies, resulting from the tag-and-probe measurement precision or from the efficiency parametrization, could affect the extraction of the polarization parameters. This effect is evaluated by applying uncertainty-based changes to the used efficiencies. The systematic uncertainty resulting from the unknown background angular distribution under the signal peak is evaluated using the measured data, by changing the relative weights of the low- and high-mass sidebands in the background model between 0.25 and 0.75, very different from the measured values of ≈0.5. The resulting uncertainty is negligible, as expected given the small magnitude of the background and the proximity of the mass sidebands to the charmonia peaks. The systematic uncertainty associated with the definition of the prompt-signal region is evaluated as the difference between the MC simulation results obtained

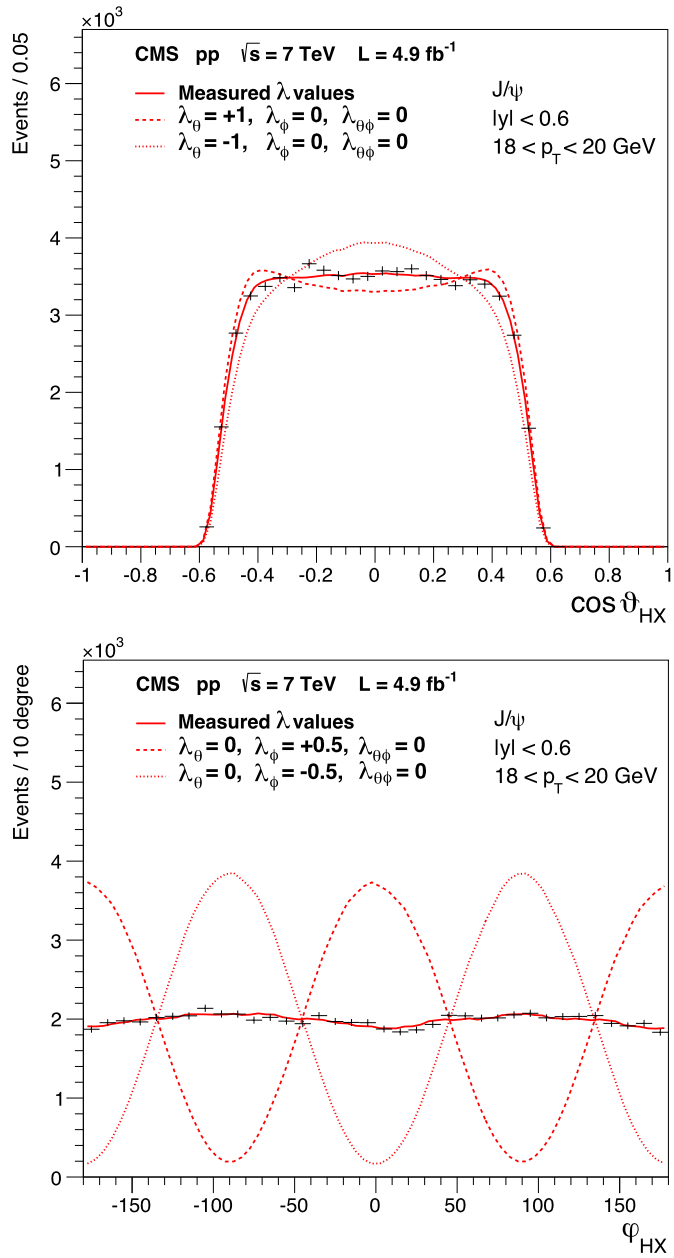

Fig. 4. Frequency distributions of $\cos\vartheta$ (top) and φ (bottom) angular variables, in the HX frame for the J/ψ in an intermediate p_T bin and $|y| < 0.6$. The curves represent the expected distributions for two extreme polarization scenarios (dashed and dotted lines defined in the legends) and for the measured $\vec{\lambda}$ (solid lines).

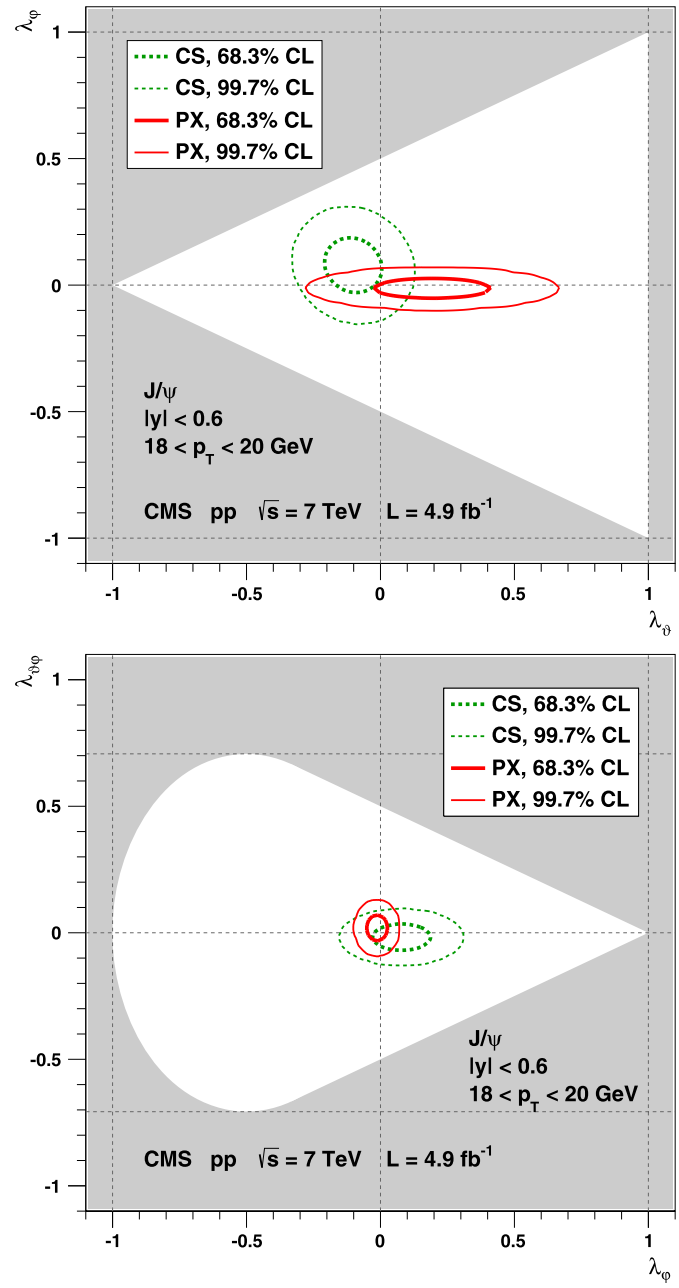

Fig. 5. Two-dimensional marginals of the PPD in the λ_φ vs. λ_ϑ (top) and $\lambda_{\vartheta\varphi}$ vs. λ_φ (bottom) planes, for J/ψ with $|y| < 0.6$ and $18 < p_T < 20$ GeV. The 68.3% and 99.7% CL total uncertainties are shown for the CS and PX frames. The shaded areas represent physically forbidden regions of parameter space [12].

with a $\pm 3\sigma_\ell$ window and with no pseudo-proper-lifetime requirement.

The $\psi(2S)$ polarization uncertainties are dominated by statistics limitations in all $(p_T, |y|)$ bins. In the J/ψ case, at high p_T the uncertainties are dominated by the statistical accuracy, while for $p_T \lesssim 30$ GeV they are determined by systematic effects. The largest among these include the single-muon ($\approx$0.1, 0.02, and 0.03) and dimuon ($\approx$0.05, 0.03, and 0.02) efficiencies, and the prompt-region definition ($\approx$0.03, 0.02, and 0.01); the values given correspond to the systematic uncertainties for λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$, respectively, in the HX frame, averaged over the rapidity bins.

The final PPD of the polarization parameters is the average of the PPDs corresponding to all hypotheses considered in the determination of the systematic uncertainties. The central value of each polarization parameter, for each kinematic bin, is evaluated as the mode of the associated one-dimensional marginal posterior, which is calculated by numerical integration. The corresponding uncertainties, at a given confidence level (CL), are given by the $[\lambda_1, \lambda_2]$ intervals, defined such that each of the regions $[-\infty, \lambda_1]$ and $[\lambda_2, \infty]$ integrates to half of $(1 - \mathrm{CL})$ of the marginal PPD. Two-dimensional marginal posteriors provide information about correlations between the measurements of the three λ parameters. As an example, Fig. 5 shows the two-dimensional marginals for λ_φ vs. λ_ϑ (top) and $\lambda_{\vartheta\varphi}$ vs. λ_φ (bottom) measured from J/ψ at $|y| < 0.6$ and $18 < p_T < 20$ GeV, displaying the 68.3% and 99.7% CL contours for the CS and PX frames. The figure also indicates the physically allowed regions for the decay of a $J = 1$ particle; this region does not affect the calculation of the PPD anywhere in the

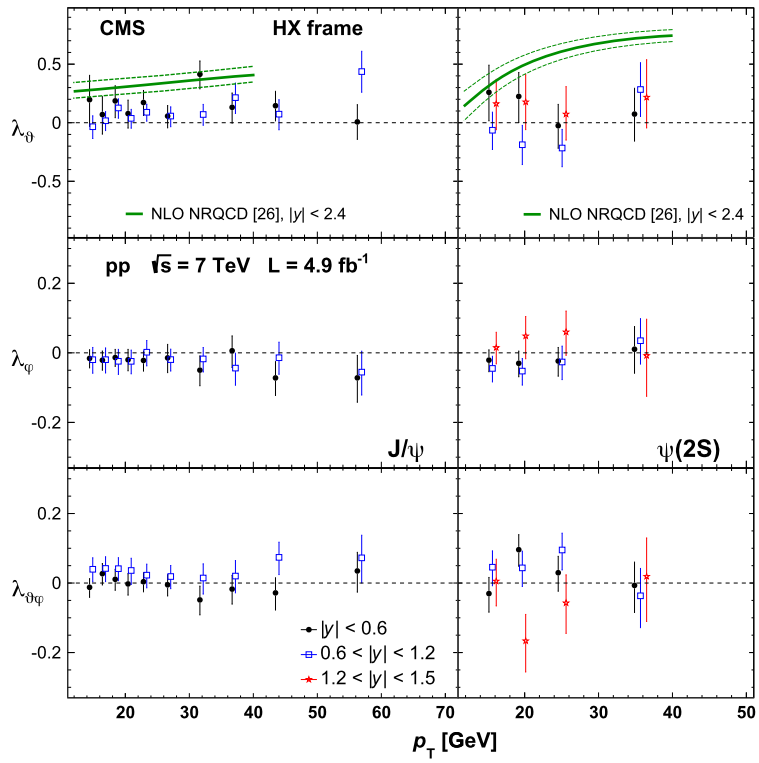

Fig. 6. Polarization parameters λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$ measured in the HX frame for prompt J/ψ (left) and $\psi(2S)$ (right) mesons, as a function of p_T and for several $|y|$ bins. The error bars represent total uncertainties (at 68.3% CL). The curves in the top two panels represent calculations of λ_ϑ from NLO NRQCD [26], the dashed lines illustrating their uncertainties.

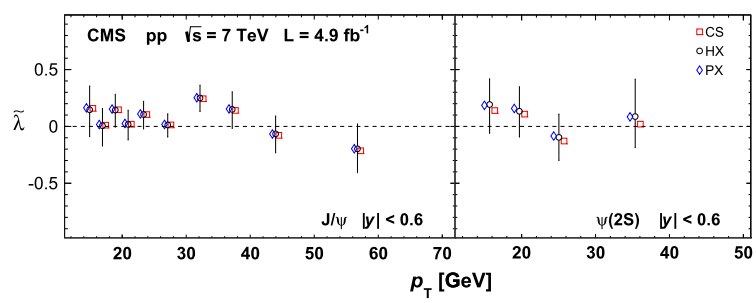

Fig. 7. Values of the frame-independent parameter $\tilde{\lambda}$ for the J/ψ (left) and $\psi(2S)$ (right) measured in the CS, HX, and PX frames, as a function of p_T and for $|y| < 0.6$. The error bars represent total uncertainties (at 68.3% CL).

analysis. For visibility reasons, the HX curves are not shown; in the phase space of this analysis (mid-rapidity and relatively high p_T), the HX and PX frames are almost identical.

4. Results

The frame-dependent λ parameters measured in the HX frame are presented, for both charmonia, in Fig. 6, as a function of p_T and $|y|$. The average values of p_T and $|y|$ are given in the supplemental material. The solid curves in the top two panels of Fig. 6 represent next-to-leading order (NLO) NRQCD calculations [26] of the λ_ϑ parameter for prompt J/ψ and $\psi(2S)$ mesons as a function of p_T for $|y| < 2.4$. The dashed lines give an estimate of the uncertainties in the theoretical predictions. The measured values of λ_ϑ are in clear disagreement with these NLO NRQCD calculations. Fig. 7 displays the frame-invariant parameter, $\tilde{\lambda}$, measured in the CS, HX, and PX frames, for the rapidity range $|y| < 0.6$. The three sets of $\tilde{\lambda}$ measurements are in good agreement, as required in the absence of unaddressed systematic effects; the same consistency is also observed in the other rapidity bins. All the results for λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$, and $\tilde{\lambda}$, for the two $\psi(nS)$ states and in the three frames considered in this analysis, including the total 68.3%, 95.5%, and 99.7% CL uncertainties and the 68.3% CL statistical uncertainties, are tabulated in the supplemental material.

None of the three polarization frames shows large polarizations, excluding the possibility that a significant polarization could remain undetected because of smearing effects induced by inappropriate frame choices [8]. While a small prompt J/ψ polarization can be interpreted as reflecting a mixture of directly produced mesons with those produced in the decays of heavier (P-wave) charmonium states, this explanation cannot apply to the $\psi(2S)$ state, unaffected by feed-down decays from heavier charmonia.

5. Summary

In summary, the polarizations of prompt J/ψ and $\psi(2S)$ mesons produced in pp collisions at $\sqrt{s} = 7$ TeV have been determined as a function of the $\psi(nS)$ p_T in two or three rapidity ranges, extending well beyond the domains probed by previous experiments, and in three different polarization frames, using both

frame-dependent and frame-independent parameters. All the measured λ parameters are close to zero, excluding large polarizations in the explored kinematic regions. These results are in clear disagreement with existing NLO NRQCD calculations [26–28] and provide a good basis for significant improvements in the understanding of quarkonium production in high-energy hadron collisions.

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Appendix A. Supplementary material

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