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Υ(nS) polarizations versus particle multiplicity in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration*

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Abstract

The polarizations of the Υ(1S), Υ(2S), and Υ(3S) mesons are measured as a function of the charged particle multiplicity in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$. The measurements are performed with a dimuon data sample collected in 2011 by the CMS experiment, corresponding to an integrated luminosity of $4.9\,\text{fb}^{-1}$. The results are extracted from the dimuon decay angular distributions, in two ranges of Υ(nS) transverse momentum (10–15 and 15–35 GeV), and in the rapidity interval $|y| < 1.2$. The results do not show significant changes from low- to high-multiplicity pp collisions, although large uncertainties preclude definite statements in the Υ(2S) and Υ(3S) cases.

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1 Introduction

Studies of heavy-quarkonium production contribute to an improved understanding of hadron formation within the context of quantum chromodynamics (QCD) [1]. Quarkonium production is expected to proceed in two steps [2]. First, a heavy quark-antiquark pair, $Q\overline{Q}$, is produced, with angular momentum L and spin S. Then this "pre-resonance" binds into the measured quarkonium state through a nonperturbative evolution that may change L and/or S. The short-distance $Q\overline{Q}$ production cross sections (SDCs) are functions of the $Q\overline{Q}$ momentum and are calculated in perturbative QCD [3–6], while the probabilities that $Q\overline{Q}$ pairs of different quantum properties form the observed quarkonium state are parametrized by momentum-independent long-distance matrix elements (LDMEs). Since they are expected to scale with powers of the heavy-quark velocity squared, v^2, in the nonrelativistic limit ($v^2 \ll 1$) most LDMEs are negligible and S-wave vector quarkonia should be dominantly formed from $Q\overline{Q}$ pairs produced as color-singlet, ${}^3S_1^{[1]}$, or as one of the ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ color-octet states. While the colour-singlet LDME can be calculated with potential models, the others, reflecting the complexity of the evolution of a coloured QCD system into a formed hadron, are determined through phenomenological analyses of quarkonium production data [3–7]. Polarization data play a central role in these analyses [7], which are performed in the zero-momentum frame of the quarkonium state (and, approximately, of the $Q\overline{Q}$ pair) and can directly reveal the quantum properties of the $Q\overline{Q}$, relying in most cases only on basic angular-momentum analysis. For example, ${}^1S_0^{[8]}$ $Q\overline{Q}$ states evolve into unpolarized ${}^3S_1$ quarkonia, while ${}^3S_1^{[8]}$ states, with quantum numbers identical to those of a gluon, lead to transversely polarized ${}^3S_1$ quarkonia.

The factorization hypothesis of nonrelativistic QCD implicitly assumes that the LDMEs are universal constants, independent of the short-distance process that created the $Q\overline{Q}$: the same LDMEs should be extracted from proton-(anti)proton and e^+e^- data, for example. However, cross section and polarization measurements at high transverse momentum, p_T, are currently limited to pp collisions, so that the LDME universality hypothesis remains a nontrivial assumption requiring direct experimental investigation. Since the nonperturbative quarkonium formation process involves interactions with the QCD medium surrounding the $Q\overline{Q}$ state, allowing it to neutralize its net colour through emission or absorption of soft gluons, it is important to verify if the polarizations (directly related to the LDMEs) depend on the complexity of the hadronic environment created by the collision. Probing if the polarizations are affected by an increase in the multiplicity of particles produced in pp collisions, the topic of the present analysis, is a first step in such a study, to be followed by analogous investigations using proton-nucleus and nucleus-nucleus data collected at different collision centralities. Such studies are crucial for a reliable interpretation of the quarkonium suppression patterns seen in high-energy nuclear collisions (see Ref. [8] and references therein) and of their relation to signatures of quark-gluon plasma formation [9–11]. While changes in integrated yields or in p_T and rapidity, y, distributions can be caused by effects such as modified parton densities in the nucleus or parton energy loss, the observation of changes in quarkonium polarization would be a direct signal of a modification in the bound-state formation mechanism.

This Letter reports how the polarizations of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons produced in pp collisions at a center-of-mass energy of 7 TeV change as a function of charged particle multiplicity, N_{ch}. It complements the observation that the $\Upsilon(nS)$ cross sections change with N_{ch}, both relative to the N_{ch}-integrated values and to the $\Upsilon(1S)$ ground state, in pp and pPb collisions [12]. The measurements are performed using a dimuon data sample collected in 2011 by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of 4.9 fb^{-1}, and follow the analysis method used in the N_{ch}-integrated measurement [13]. The

dimuon mass distribution is used to separate the $\Upsilon(\mathrm{nS})$ signals from each other and from muon pairs due to other processes, such as decays of heavy flavor mesons. The $\Upsilon(\mathrm{nS})$ polarizations are characterized through three parameters, $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$, reflecting the anisotropy of the angular distribution of the decay muons [14],

$$W(\cos\vartheta, \varphi|\vec{\lambda}) \propto \frac{1}{(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi), \tag{1}$$

where ϑ and φ are the polar and azimuthal angles, respectively, of the μ^+. These $\vec{\lambda}$ parameters, as well as the frame-invariant parameter $\tilde{\lambda} = (\lambda_\vartheta + 3\,\lambda_\varphi)/(1 - \lambda_\varphi)$ [15], are measured in the center-of-mass helicity frame (HX), where the z axis coincides with the direction of the Υ momentum. The y axis of the polarization frame is reversed between positive and negative rapidity, a definition that avoids the cancellation of $\lambda_{\vartheta\varphi}$ when integrating events over a symmetrical range in rapidity. This is explained in Ref. [16], which provides a pedagogical introduction to quarkonium polarization physics. As in the previous CMS quarkonium polarization measurements [13, 17], the analysis is exclusively based on measured data: the 3-momentum vectors of the two muons (containing the spin alignment information of the decaying $\Upsilon(\mathrm{nS})$ mesons) and the muon detection efficiencies.

2 CMS detector and data analysis

The CMS apparatus is based on 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 and scintillator hadron calorimeter. Muons are measured with drift tubes, cathode strip chambers, and resistive-plate chambers. The main detectors used in this analysis are the silicon tracker and the muon system, which enable the measurement of muon momenta over the pseudorapidity range $|\eta| < 2.4$. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [18]. The events were collected using a two-level trigger system. The first level uses custom hardware processors to select events with two muons. The high-level trigger, adding information from the silicon tracker, selects opposite-sign muon pairs of invariant mass $8.5 < M < 11.5\,\mathrm{GeV}$, $|y| < 1.25$ and $p_\mathrm{T} > 7\,\mathrm{GeV}$; the dimuon vertex fit χ^2 probability must exceed 0.5% and the two muons must have a distance of closest approach smaller than 5 mm. No p_T requirement is imposed on the single muons.

The offline analysis selects muon tracks with hits in more than ten tracker layers, at least two of which are in the pixel layers, and matched with segments in the muon system. They must have a good track fit quality, point to the interaction region, and match the muon objects that triggered the event. The selected muons are required to satisfy $|\eta| < 1.6$ and to have p_T above 4.5, 3.5, and 3 GeV for $|\eta| < 1.2$, $1.2 < |\eta| < 1.4$, and $1.4 < |\eta| < 1.6$, respectively, to ensure reliable detection and trigger efficiencies. The combinatorial background from uncorrelated muons is suppressed by requiring a dimuon vertex fit χ^2 probability larger than 1% and a distance between the dimuon and the primary vertex smaller than twice its uncertainty. In events with multiple reconstructed primary vertices (pileup), the one nearest to the point of closest approach between the trajectory of the dimuon and the beam line is selected. The N_ch variable is computed by counting "high purity" [19] charged tracks, excluding the two muons, of $|\eta| < 2.4$, $p_\mathrm{T} > 500\,\mathrm{MeV}$, and p_T measured with better than 10% relative accuracy. Acceptance and reconstruction efficiencies are not corrected for. Each track is assigned a weight reflecting the likelihood that it belongs to the primary vertex [19]; tracks consistent with the vertex have a weight close to unity. The migration of events from one N_ch bin to the next, caused by inadvertently counting spurious tracks produced in near-by pileup vertices, is kept negligible by

rejecting events with more than 16 vertices. Figure 1 shows the N_{ch} distribution of the events selected in this analysis.

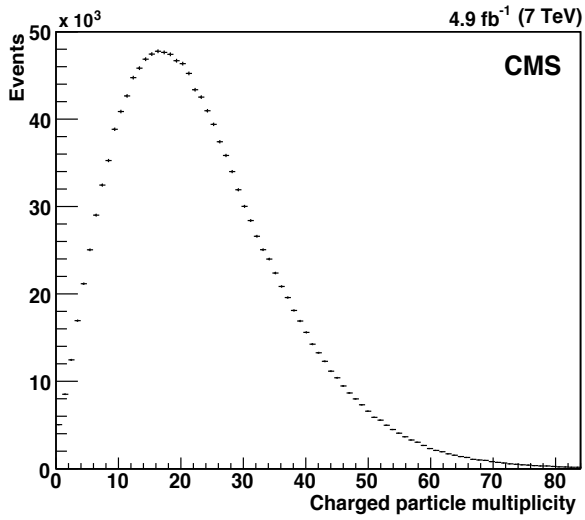

Figure 1: Charged particle multiplicity distribution of the events selected for the analysis.

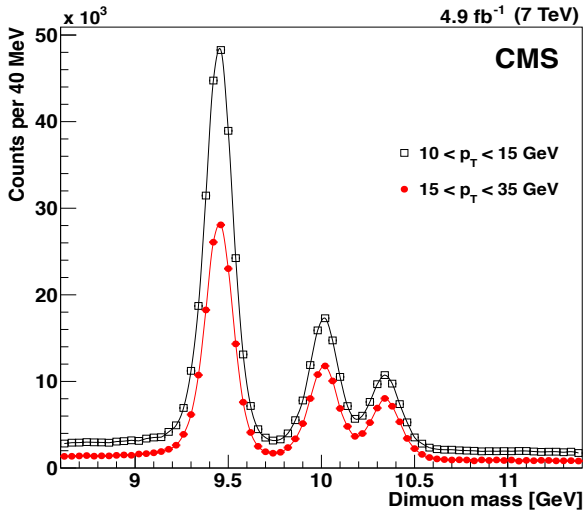

Figure 2: Dimuon mass distributions in the $\Upsilon(\mathrm{nS})$ region for two p_{T} ranges.

The dimuon mass distribution, shown in Fig. 2, is well described by three Crystal-Ball functions [20], one per $\Upsilon(\mathrm{nS})$ peak, and a second-order polynomial function representing the underlying continuum, determined from the mass sidebands, 8.6–8.9 and 10.6–11.4 GeV. The dimuon mass resolution is $\sigma \approx 80$ MeV, slightly dependent on p_{T}. The $\Upsilon(\mathrm{nS})$ signal mass regions are defined as the $\pm 1\,\sigma$ windows around the nominal $\Upsilon(\mathrm{nS})$ masses. The corresponding cross-feed between the three peaks is negligible. The analysis is performed in five N_{ch} bins, 0–10, 10–20, 20–30, 30–40, and 40–60, sufficiently numerous and narrow to probe potential variations of the polarizations, and in two $\Upsilon(\mathrm{nS})$ p_{T} ranges, 10–15 and 15–35 GeV. The dimuons are integrated within $|y| < 1.2$. The lower p_{T} $\Upsilon(3\mathrm{S})$ polarization measurement merges the two highest N_{ch} bins, to reduce the background-related systematic uncertainties. In the lowest N_{ch} bin, the background fractions in the signal mass regions, f_{Bg}, are approximately 3%, 7%, and 10% for the $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(3\mathrm{S})$, respectively. The corresponding values in the highest N_{ch} bin are $\sim$4 and $\sim$2.5 times higher in the 10–15 and 15–35 GeV p_{T} ranges, respectively. All analysis bins have signal yields sufficiently high for a reliable measurement, the worst case being the 2300 $\Upsilon(3\mathrm{S})$ events in the highest N_{ch} bin at high p_{T}. All signal yields and background fractions are

tabulated in Appendix A.

The single-muon detection efficiencies are measured with a "tag-and-probe" technique [21], using event samples collected with triggers specifically designed for this purpose, including a sample enriched in dimuons from J/ψ decays where a muon is combined with another track and the pair is required to have an invariant mass within 2.8–3.4 GeV. The procedure was validated with detailed Monte Carlo simulation studies. The measured efficiencies are parametrized as a function of muon p_{T}, in eight $|\eta|$ bins. Their uncertainties, ∼2–3%, reflecting the statistical precision of the calibration samples and possible imperfections of the parametrization, are independent of N_{ch} and identical for the three Υ(nS) states. These global uncertainties do not affect the search for potential variations of the polarizations from low- to high-multiplicity events. The trigger and the selection criteria could potentially introduce differences between the dimuon detection efficiencies and the product of the efficiencies of the two single muons. Simulation studies reveal that such correlations have a negligible dependence on $\cos\vartheta$ and φ, in the phase space of this analysis [13]. Residual effects contribute to the global systematic uncertainties [13].

3 Extraction of the polarization parameters

The two-dimensional angular distribution, in $\cos\vartheta$ and φ, of the background corresponding to a given Υ(nS) state is evaluated as a weighted average of the distributions measured in the two mass sidebands, the weights reflecting (linearly) the differences between the Υ(nS) mass and the median masses of the sidebands. The background component is subtracted on an event-by-event basis using a likelihood-ratio criterium, randomly selecting and removing a fraction f_{Bg} of events distributed according to the $(p_{\mathrm{T}}, |y|, M, \cos\vartheta, \varphi)$ distribution of the background model [13]. The posterior probability density (PPD) for the average values of the Υ(nS) polarization parameters ($\vec{\lambda}$) inside a particular bin is then defined as a product over the remaining (signal-like) events i,

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

where $\mathcal{E}$ represents the event probability distribution as a function of the muon momenta $\vec{p}_{1,2}$ in event i. This analysis method does not use model-dependent $(\cos\vartheta, \varphi)$ acceptance maps; each event is attributed a probability reflecting the full event kinematics (not only $\cos\vartheta$ and φ) and the values of the polarization parameters,

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

where $\epsilon(\vec{p}_1, \vec{p}_2)$ is the measured detection efficiency. The normalization factor $\mathcal{N}(\vec{\lambda})$ is calculated by integrating $W \cdot \epsilon$ over $\cos\vartheta$ and φ uniformly, using $(p_{\mathrm{T}}, |y|, M)$ distributions determined from the background-subtracted data. To account for the statistical fluctuations related to its random nature, the background subtraction procedure is repeated 50 times.

Figure 3 compares the $\cos\vartheta$ and φ distributions measured for Υ(2S) signal events of $15 < p_{\mathrm{T}} < 35$ GeV and $10 < N_{\mathrm{ch}} < 20$ with curves reflecting the "best fit" as well as, for illustration, two scenarios corresponding to the λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$ values reported in the legends of the plots.

Each of the systematic uncertainties on the polarization parameters caused by the analysis framework and the detection efficiencies is individually evaluated through 50 statistically independent pseudo-experiments. For each effect, the systematic uncertainty is the difference between the injected and resulting parameters. The robustness of the framework to measure

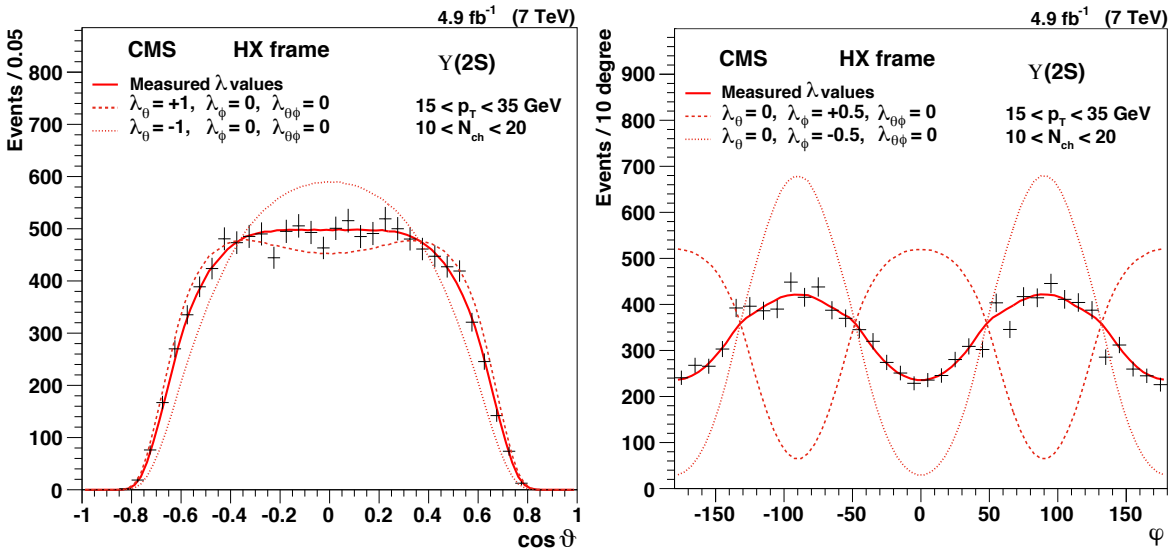

Figure 3: Distributions of $\cos\vartheta$ (left) and φ (right), for the $\Upsilon(2S)$ in a representative analysis bin. The curves represent two polarization scenarios (dashed and dotted lines, defined in the legends) and the measured case (solid lines: $\lambda_\vartheta = 0.237$, $\lambda_\varphi = -0.027$, $\lambda_{\vartheta\varphi} = -0.025$).

the signal polarization is validated for several signal and background polarization scenarios. The impact of residual biases that could be caused by uncertainties on the muon or dimuon efficiencies is evaluated by extracting the polarization parameters after applying corresponding variations to the input efficiencies. The background model uncertainty is evaluated by modifying the relative weights of the low- and high-mass sidebands when building the background distributions. A broad range of hypotheses is considered, including the assumption that the background under the $\Upsilon(1S)$ ($\Upsilon(3S)$) peak resembles exclusively the low-mass (high-mass) sideband, or assuming that it is reproduced by an equal mixture of the two sideband distributions. Several systematic uncertainties have similar levels, except in the highest N_{ch} bins and the lowest p_T range, where the background model uncertainty dominates, especially for the $\Upsilon(2S)$ and $\Upsilon(3S)$ states. For the $\Upsilon(1S)$ state and in the HX frame, the N_{ch}-dependent systematic uncertainties are $\sim$0.1 for λ_ϑ and $\sim$0.03–0.05 for λ_φ and $\lambda_{\vartheta\varphi}$, slightly increasing with N_{ch}. The corresponding $\Upsilon(2S)$ and $\Upsilon(3S)$ values are slightly larger: $\sim$0.2 for λ_ϑ, $\sim$0.04 for λ_φ, and $\sim$0.05–0.08 for $\lambda_{\vartheta\varphi}$. The statistical uncertainties are negligible for the $\Upsilon(1S)$ state and become dominant for the $\Upsilon(2S)$ and $\Upsilon(3S)$ states, as N_{ch} increases.

4 Results

The final PPD of the polarization parameters is an envelope of the PPDs corresponding to all hypotheses considered in the evaluation of the systematic uncertainties. In each analysis bin, the central values and 68.3% confidence level (CL) uncertainties of each polarization parameter are evaluated from the corresponding one-dimensional marginal posterior, calculated by numerical integration. In the HX frame, the λ parameters are measured with negligible correlations, as illustrated by Fig. 4, which shows the two-dimensional marginals of the PPD in the λ_φ vs. λ_ϑ and $\lambda_{\vartheta\varphi}$ vs. λ_φ planes, for a representative analysis bin.

Figure 5 shows the λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$, and $\tilde{\lambda}$ values measured in the HX frame for the three $\Upsilon(nS)$ states, in both p_T ranges. The corresponding numerical results are tabulated in Appendix A. The $\tilde{\lambda}$ values have also been measured in the Collins–Soper frame (CS) [22], whose z axis is the average of the two beam directions in the Υ rest frame, and in the perpendicular helicity frame

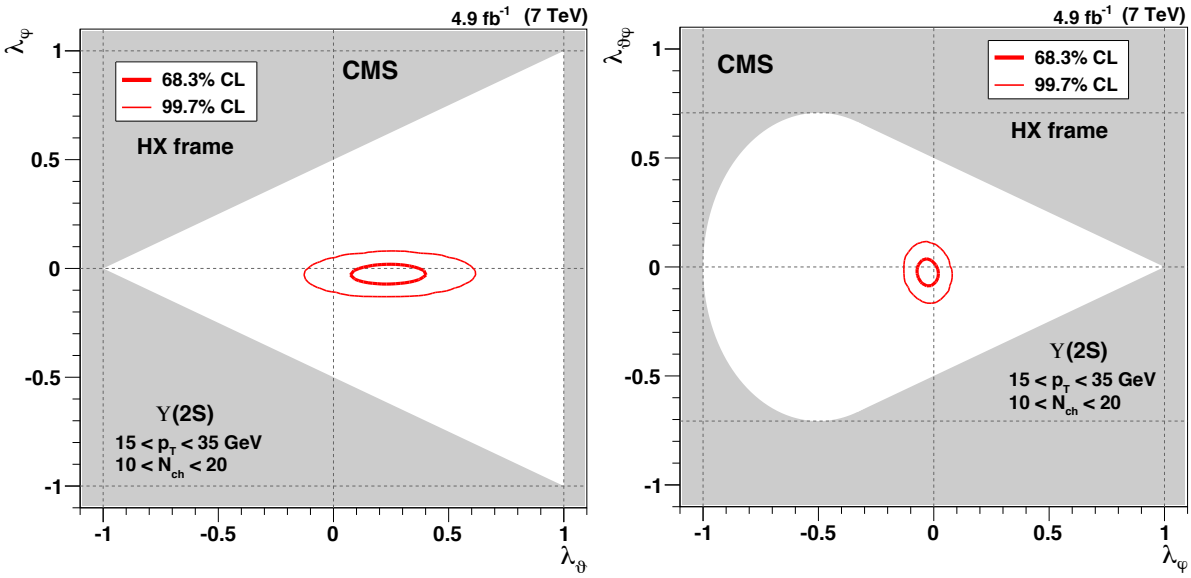

Figure 4: Two-dimensional marginals of the PPD for the HX frame in the λ_φ vs. λ_ϑ (left) and $\lambda_{\vartheta\varphi}$ vs. λ_φ (right) planes, for $\Upsilon(2S)$ with $15 < p_T < 35\,\text{GeV}$ and $10 < N_{ch} < 20$, displaying the 68.3% and 99.7% CL total uncertainties. The shaded areas represent physically forbidden regions of parameter space for the decay of a $J = 1$ particle [14].

(PX) [23], orthogonal to the CS frame. The three measurements agree with each other, within systematic uncertainties (similar in all frames), as required in the absence of unaccounted systematic effects [24].

Regarding the $\Upsilon(1S)$ results, all the λ parameters are close to zero, indicating essentially unpolarized production, as expected if the mesons included in this analysis would be dominantly produced through the unpolarized ${}^1S_0^{[8]}$ pre-resonant octet state. The trend as a function of N_{ch} does not indicate any strong changes in $\Upsilon(1S)$ production between low- and high-multiplicity pp collisions. The measurements are compatible with a non-negligible fraction of $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons being produced via the transversely polarized ${}^3S_1^{[8]}$ octet term. Given the present uncertainties, no clear trends can be seen regarding changes of their polarizations with N_{ch}.

To place these results into context, Fig. 6-left illustrates how the λ_ϑ parameter would change as a function of N_{ch} if quarkonium production would be dominated by two processes, one unpolarized ($\lambda_\vartheta = 0$, as is the case for the ${}^1S_0^{[8]}$ octet) and the other fully transversely polarized in the HX frame ($\lambda_\vartheta = +1$, as for the ${}^3S_1^{[8]}$ octet, at high enough p_T). The four curves represent different variations with N_{ch} (linearly in the $0 < N_{ch} < 60$ range) of the fraction of events, f, produced through the latter process (defined in the legends). These curves were computed knowing that the polarization of a sample of quarkonium states produced through two different processes, of polarizations λ_0 and λ_1, depends on f as [25]

$$\lambda(f) = \left[\frac{(1-f)\,\lambda_0}{3+\lambda_0} + \frac{f\,\lambda_1}{3+\lambda_1}\right] \Big/ \left[\frac{1-f}{3+\lambda_0} + \frac{f}{3+\lambda_1}\right]. \tag{4}$$

Changes in the LDMEs, in particular of the dominant ${}^1S_0^{[8]}$ and ${}^3S_1^{[8]}$ octet terms [7], are not the only possible cause of variations in the measured $\Upsilon(nS)$ λ parameters between low- and high-multiplicity pp collisions; the effects of feed-down decays from heavier quarkonia should also be considered. In fact, the polarizations reported here correspond to inclusive $\Upsilon(nS)$ samples, not distinguishing mesons emitted in the decays of S- and P-wave bottomonium states from

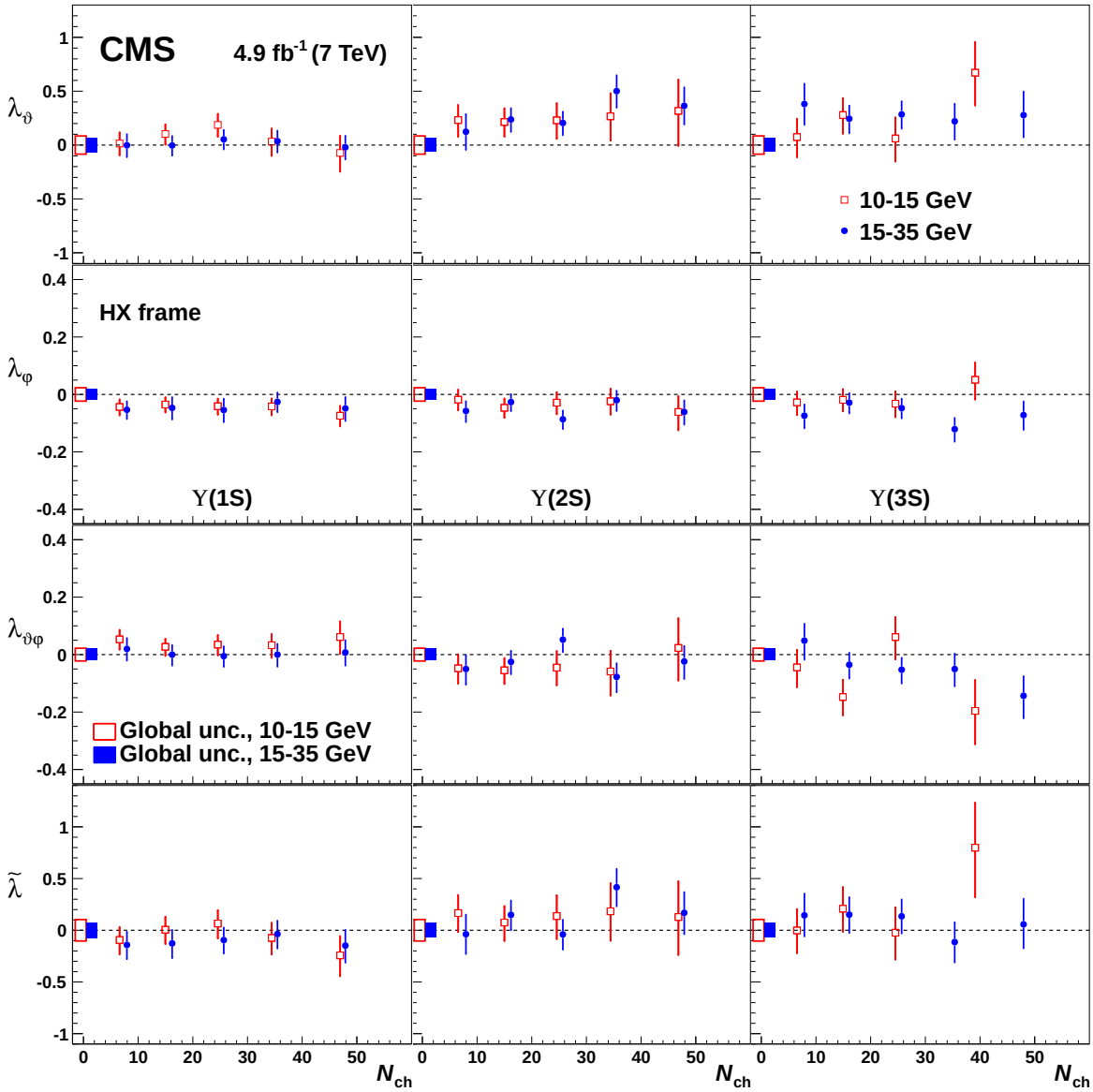

Figure 5: The λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$, and $\tilde{\lambda}$ parameters (top to bottom) for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states (left to right), in the HX frame, as a function of N_{ch}, for both p_T ranges. The vertical bars represent the N_{ch}-dependent total uncertainties (at 68.3% CL), while the boxes at the zero horizontal line represent the global uncertainties. The points are placed at the average N_{ch} of each bin, with a small offset for easier viewing.

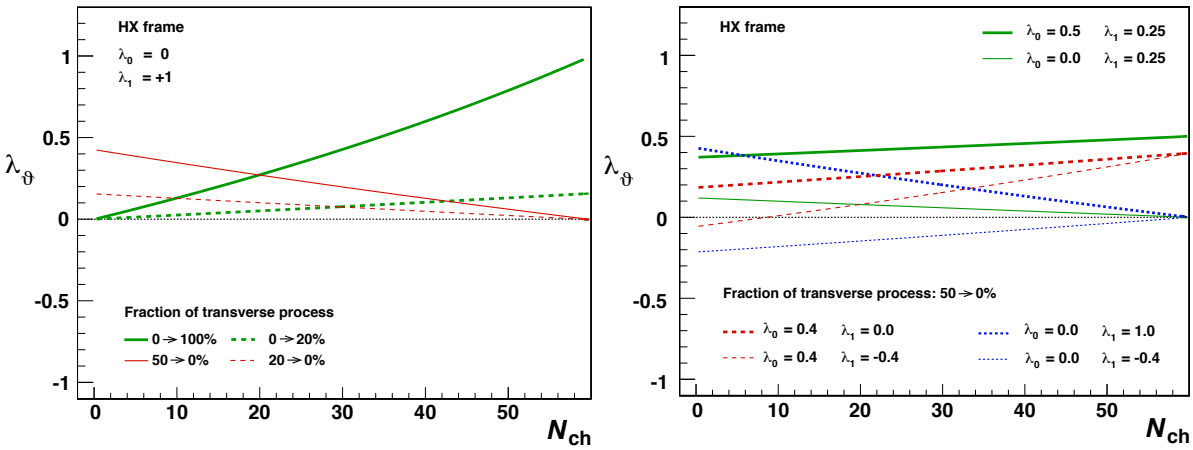

Figure 6: Expected N_{ch}-dependences of the λ_ϑ parameter for the sum of two processes, of polarizations λ_0 and λ_1, of relative fractions changing linearly with N_{ch} (see text for details).

the directly-produced ones. Assuming that all directly-produced S-wave states have identical polarizations, their decays to lighter S-wave states do not induce differences between the measured (inclusive) polarizations and those of the directly-produced mesons. On the contrary, feed-down decays from P-wave states can significantly affect the measured values, especially for the $\Upsilon(1S)$ state, presumably the one affected by the largest feed-down fraction. It is presently not possible to reliably evaluate the influence of the feed-down decays on the measured $\Upsilon(nS)$ polarizations, for lack of information regarding the χ_b polarizations and their feed-down fractions. Figure 6-right shows how the measured (inclusive) polarization is expected to change as a function of N_{ch} if the directly-produced component (of polarization λ_0) is complemented by a feed-down component (of polarization λ_1) that contributes with a fraction f, decreasing linearly with N_{ch} from 50% to 0 in the $0 < N_{ch} < 60$ range. The six curves correspond to different assumptions for λ_0 and λ_1, reported in the legends, with λ_1 representing an effective average of the χ_{b1} and χ_{b2} polarizations (bound to $\lambda_\vartheta > -1/3$ and $\lambda_\vartheta > -3/5$, respectively [25]). In these scenarios the feed-down fraction is assumed to become negligible at high N_{ch}, where the inclusive λ_ϑ tends to the direct λ_0 value. At low N_{ch}, where the feed-down contribution is, hypothetically, the highest, the inclusive λ_ϑ parameter crucially depends on the assumed χ_b polarization.

5 Summary

The polarizations of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons produced in pp collisions at $\sqrt{s} = 7$ TeV have been determined as functions of the charged particle multiplicity of the event in two $\Upsilon(nS)$ p_T ranges. The measurements do not show significant variations as a function of N_{ch}, even though the large $\Upsilon(2S)$ and $\Upsilon(3S)$ uncertainties preclude definite statements in these cases. This study opens the way for analogous measurements extending to the charmonium family, particularly interesting for the $\psi(2S)$, which is unaffected by feed-down decays and, therefore, provides a more direct probe of LDME universality. Equivalent analyses should also be performed in pPb and PbPb event samples, in view of evaluating how quark-antiquark bound-state formation is influenced by the surrounding medium, which is an essential input for the interpretation of quarkonium suppression patterns in nuclear collisions.

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A Supplemental material

Table 1: Signal yields, N, and background fractions, f_{Bg} (in %), within 1σ windows around the nominal $\Upsilon(\mathrm{nS})$ masses for the considered N_{ch} and p_{T} ranges.

p_{T} [GeV]	N_{ch}	$\Upsilon(1S)$		$\Upsilon(2S)$		$\Upsilon(3S)$	
		N	f_{Bg}	N	f_{Bg}	N	f_{Bg}
10–15	0–10	26 900	3	10 200	7	6 500	10
	10–20	51 300	5	18 200	12	10 800	18
	20–30	39 200	7	13 000	18	7 500	26
	30–40	20 100	9	6 300	24	5 200	40
	40–60	11 300	12	3 400	31		
15–35	0–10	10 600	3	4 500	7	3 200	9
	10–20	27 900	4	12 100	9	8 200	12
	20–30	25 700	5	10 900	11	7 200	15
	30–40	15 100	6	6 300	14	3 800	20
	40–60	9 500	7	3 400	17	2 300	24

Table 2: $\Upsilon(\mathrm{nS})$ polarization parameters in the HX frame. The global uncertainties, independent of state and N_{ch} bin, are also indicated.

State	p_{T} [GeV	N_{ch}	λ_ϑ	λ_φ	$\lambda_{\vartheta\varphi}$	$\tilde{\lambda}$
Υ(1S)	10–15	0–10	$+0.014^{+0.102}_{-0.110}$	$-0.044^{+0.026}_{-0.029}$	$+0.053^{+0.033}_{-0.036}$	$-0.094^{+0.126}_{-0.138}$
		10–20	$+0.103^{+0.089}_{-0.098}$	$-0.035^{+0.025}_{-0.027}$	$+0.027^{+0.028}_{-0.031}$	$+0.005^{+0.126}_{-0.139}$
		20–30	$+0.187^{+0.102}_{-0.110}$	$-0.041^{+0.026}_{-0.029}$	$+0.035^{+0.033}_{-0.037}$	$+0.066^{+0.128}_{-0.145}$
		30–40	$+0.032^{+0.121}_{-0.132}$	$-0.042^{+0.027}_{-0.031}$	$+0.033^{+0.039}_{-0.044}$	$-0.074^{+0.146}_{-0.159}$
		40–60	$-0.073^{+0.159}_{-0.174}$	$-0.074^{+0.034}_{-0.037}$	$+0.061^{+0.054}_{-0.059}$	$-0.243^{+0.186}_{-0.201}$
Υ(2S)	10–15	0–10	$+0.232^{+0.140}_{-0.156}$	$-0.018^{+0.035}_{-0.037}$	$-0.048^{+0.049}_{-0.054}$	$+0.166^{+0.174}_{-0.183}$
		10–20	$+0.214^{+0.126}_{-0.136}$	$-0.047^{+0.032}_{-0.035}$	$-0.055^{+0.042}_{-0.048}$	$+0.075^{+0.158}_{-0.178}$
		20–30	$+0.230^{+0.158}_{-0.171}$	$-0.028^{+0.036}_{-0.040}$	$-0.045^{+0.057}_{-0.061}$	$+0.137^{+0.201}_{-0.222}$
		30–40	$+0.267^{+0.213}_{-0.226}$	$-0.024^{+0.044}_{-0.046}$	$-0.059^{+0.072}_{-0.084}$	$+0.183^{+0.272}_{-0.284}$
		40–60	$+0.317^{+0.289}_{-0.325}$	$-0.061^{+0.055}_{-0.063}$	$+0.023^{+0.103}_{-0.113}$	$+0.128^{+0.345}_{-0.366}$
Υ(3S)	10–15	0–10	$+0.074^{+0.169}_{-0.187}$	$-0.028^{+0.038}_{-0.044}$	$-0.044^{+0.061}_{-0.069}$	$-0.002^{+0.205}_{-0.219}$
		10–20	$+0.279^{+0.156}_{-0.173}$	$-0.019^{+0.037}_{-0.040}$	$-0.148^{+0.060}_{-0.064}$	$+0.208^{+0.209}_{-0.223}$
		20–30	$+0.061^{+0.194}_{-0.213}$	$-0.032^{+0.043}_{-0.047}$	$+0.061^{+0.069}_{-0.078}$	$-0.023^{+0.245}_{-0.259}$
		30–60	$+0.672^{+0.285}_{-0.304}$	$+0.051^{+0.061}_{-0.068}$	$-0.196^{+0.108}_{-0.116}$	$+0.798^{+0.435}_{-0.479}$
		global unc.	±0.085	±0.023	±0.022	±0.104
Υ(1S)	15–35	0–10	$-0.002^{+0.102}_{-0.110}$	$-0.054^{+0.029}_{-0.032}$	$+0.020^{+0.038}_{-0.041}$	$-0.142^{+0.128}_{-0.138}$
		10–20	$-0.004^{+0.087}_{-0.094}$	$-0.047^{+0.037}_{-0.041}$	$-0.000^{+0.033}_{-0.038}$	$-0.127^{+0.130}_{-0.142}$
		20–30	$+0.053^{+0.087}_{-0.093}$	$-0.054^{+0.039}_{-0.042}$	$-0.005^{+0.034}_{-0.037}$	$-0.095^{+0.121}_{-0.130}$
		30–40	$+0.036^{+0.097}_{-0.105}$	$-0.026^{+0.033}_{-0.036}$	$-0.000^{+0.037}_{-0.042}$	$-0.037^{+0.128}_{-0.139}$
		40–60	$-0.021^{+0.106}_{-0.112}$	$-0.049^{+0.039}_{-0.044}$	$+0.007^{+0.043}_{-0.046}$	$-0.148^{+0.151}_{-0.164}$
Υ(2S)	15–35	0–10	$+0.124^{+0.163}_{-0.168}$	$-0.058^{+0.034}_{-0.039}$	$-0.050^{+0.048}_{-0.054}$	$-0.039^{+0.189}_{-0.190}$
		10–20	$+0.237^{+0.105}_{-0.114}$	$-0.027^{+0.028}_{-0.032}$	$-0.025^{+0.039}_{-0.043}$	$+0.149^{+0.138}_{-0.148}$
		20–30	$+0.205^{+0.104}_{-0.113}$	$-0.086^{+0.030}_{-0.034}$	$+0.052^{+0.038}_{-0.043}$	$-0.040^{+0.141}_{-0.146}$
		30–40	$+0.501^{+0.147}_{-0.153}$	$-0.020^{+0.033}_{-0.037}$	$-0.078^{+0.047}_{-0.053}$	$+0.416^{+0.177}_{-0.184}$
		40–60	$+0.364^{+0.171}_{-0.172}$	$-0.061^{+0.040}_{-0.044}$	$-0.024^{+0.053}_{-0.061}$	$+0.169^{+0.200}_{-0.206}$
Υ(3S)	15–35	0–10	$+0.381^{+0.188}_{-0.193}$	$-0.074^{+0.039}_{-0.044}$	$+0.048^{+0.059}_{-0.066}$	$+0.144^{+0.210}_{-0.203}$
		10–20	$+0.244^{+0.121}_{-0.134}$	$-0.029^{+0.033}_{-0.037}$	$-0.035^{+0.041}_{-0.048}$	$+0.151^{+0.169}_{-0.177}$
		20–30	$+0.285^{+0.121}_{-0.132}$	$-0.048^{+0.032}_{-0.036}$	$-0.053^{+0.041}_{-0.048}$	$+0.135^{+0.162}_{-0.165}$
		30–40	$+0.220^{+0.163}_{-0.169}$	$-0.121^{+0.039}_{-0.043}$	$-0.050^{+0.054}_{-0.060}$	$-0.114^{+0.191}_{-0.197}$
		40–60	$+0.278^{+0.218}_{-0.206}$	$-0.072^{+0.048}_{-0.051}$	$-0.143^{+0.068}_{-0.078}$	$+0.057^{+0.246}_{-0.231}$
		global unc.	±0.066	±0.019	±0.020	±0.073

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