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Measurement of the Υ(1S), Υ(2S), and Υ(3S) polarizations in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The polarizations of the Υ(1S), Υ(2S), and Υ(3S) mesons are measured in proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, using a data sample of $\Upsilon(\mathrm{nS}) \rightarrow \mu^+\mu^-$ decays collected by the CMS experiment, corresponding to an integrated luminosity of $4.9\,\mathrm{fb}^{-1}$. The dimuon decay angular distributions are analyzed in three different polarization frames. The polarization parameters λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$, as well as the frame-invariant quantity $\tilde{\lambda}$, are presented as a function of the Υ(nS) transverse momentum between 10 and 50 GeV, in the rapidity ranges $|y| < 0.6$ and $0.6 < |y| < 1.2$. No evidence of large transverse or longitudinal polarizations is seen in the explored kinematic region.

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*See Appendix A for the list of collaboration members

Studies of heavy-quarkonium production play a crucial role in the detailed investigation of quantum chromodynamics (QCD), from the hard region, where an expansion in the coupling constant is possible, to the soft region, dominated by nonperturbative effects [1]. Given their high mass, heavy-quarkonium states are approximately nonrelativistic systems, allowing the application of theoretical tools that simplify and constrain the analyses of nonperturbative effects [2]. The differential cross sections of J/ψ and Υ mesons produced at Tevatron [3–5] and LHC [6–8] energies can be reproduced by calculations based on nonrelativistic QCD (NRQCD) [9], dominated by "color octet" production. However, the corresponding predictions [10] of strong transverse polarizations (dominant angular momentum component $J_z = \pm 1$ with respect to the quarkonium momentum direction) are in stark disagreement with the negligible polarizations measured for the J/ψ [11]. The Υ satisfies the nonrelativistic approximation much better than the J/ψ, making the Υ polarization a more decisive test of NRQCD, especially at asymptotically large transverse momentum, p_T. The existing measurements, however, are inconclusive, with the CDF [12] and D0 [13] results in mutual contradiction.

The polarization of the ($J^{PC} = 1^{--}$) Υ states can be measured through the study of the angular distribution of the leptons produced in the $\Upsilon \to \mu^+\mu^-$ decay [14],

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

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. As pointed out in Refs. [14–18], improved experimental measurements of quarkonium polarization require measuring all the angular distribution parameters, $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$, in different polarization frames, as well as a frame-invariant polarization parameter, $\tilde{\lambda} = (\lambda_\vartheta + 3\,\lambda_\varphi)/(1 - \lambda_\varphi)$. This approach has already been followed in the Υ(nS) polarization analysis of CDF [12], and in some recent theory calculations [19].

This Letter presents the first measurement of the polarizations of the Υ(nS) mesons produced in pp collisions at a center-of-mass energy of 7 TeV. The analysis is based on a dimuon sample collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 4.9 fb^{-1} and containing 252 000 Υ(1S), 94 000 Υ(2S), and 58 000 Υ(3S) mesons (after all selection criteria).

The analysis uses an unbinned likelihood approach, independent of assumptions on the production kinematics. The results are obtained in three frames, with different directions of the quantization axis: the center-of-mass helicity (HX) frame, where the polar axis coincides with the direction of the Υ momentum; the Collins–Soper (CS) frame [20], whose axis is the average of the two beam directions in the Υ rest frame; and the perpendicular helicity (PX) frame [21], orthogonal to the CS frame. The y axis of the polarization frame is taken, in all cases, to be in the direction of the vector product of the two beam directions, $\vec{P}_1 \times \vec{P}_2$ and $\vec{P}_2 \times \vec{P}_1$ for positive and negative rapidity, respectively.

The central feature of the CMS apparatus [22] is a superconducting solenoid of 6 m internal diameter, providing a 3.8 T field. The main subdetectors used in this analysis are the silicon tracker and the muon system. The silicon tracker, composed of pixel and strip detector modules, is immersed in the magnetic field and enables the measurement of charged-particle momenta over the pseudorapidity range $|\eta| < 2.5$. Muons are measured in the range $|\eta| < 2.4$ using gas-ionization detectors embedded in the steel return yoke of the magnet and made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. 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” requires an opposite-sign muon pair with invariant mass $8.5 < M < 11.5\,\mathrm{GeV}$, $|y| < 1.25$, $p_{\mathrm{T}} > 5$ or $7\,\mathrm{GeV}$ (depending on the instantaneous luminosity), and vertex fit χ^2 probability greater than 0.5%.

In the offline analysis, dimuons are formed by combining pairs of opposite-sign muons (tracks in the silicon tracker matched to tracks in the muon detectors) that satisfy several quality criteria, including the number of tracker hits, the muon-track fit quality, and the vicinity of the track to the closest primary vertex along the beam line. The selected muons are required to satisfy $|\eta| < 1.6$ and to have p_{T} 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, to ensure accurately measured muon detection efficiencies. Subsequent to the offline trigger confirmation, the combinatorial background from uncorrelated muons is reduced by requiring a dimuon vertex fit χ^2 probability larger than 1.0% and a distance between the dimuon vertex and the closest primary vertex less than twice its uncertainty. The analysis is performed in five dimuon p_{T} bins, of edges 10, 12, 16, 20, 30, and 50 GeV, and two $|y|$ ranges, 0.0–0.6 and 0.6–1.2.

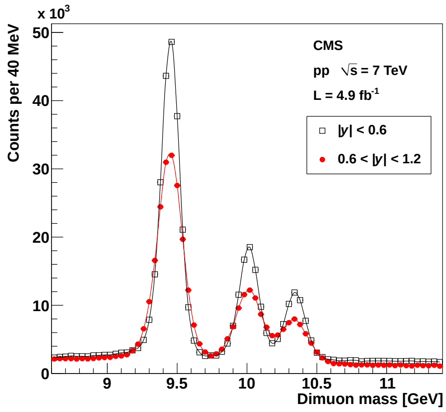

Figure 1: Dimuon mass distributions in the Υ region for $|y| < 0.6$ (open squares) and $0.6 < |y| < 1.2$ (closed circles).

The dimuon mass distribution, shown in Fig. 1, is well described by three Crystal-Ball functions [23] representing the Υ peaks, and by a second-degree polynomial function determined from the low- and high-mass sidebands, located below the $\Upsilon(1S)$ and above the $\Upsilon(3S)$, respectively. The dimuon mass resolution is better than 70 MeV for $|y| < 0.6$, increasing to 95 MeV in the $0.6 < |y| < 1.2$ range, where the $\Upsilon(2S)$ and $\Upsilon(3S)$ peaks partially overlap. Within a ± 1 standard deviation (σ) window around the $\Upsilon(nS)$ masses, the cross-feed between the $\Upsilon(2S)$ and $\Upsilon(3S)$ is below 4%, and the background fractions are 4–8%, 9–18%, and 12–28% (increasing with decreasing p_{T}), for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, respectively.

The single-muon detection efficiencies are measured with a “tag-and-probe” technique [24] using event samples collected with dedicated triggers enriched in dimuons from J/ψ decays. The trigger and reconstruction efficiencies must be accurately determined to avoid biases on the angular distributions, which could mimic polarization effects. The technique has been validated in the fiducial region of the analysis with detailed Monte Carlo (MC) simulation studies. The single-muon efficiencies are measured and parametrized as a function of p_{T} in eight η bins. Their uncertainties, reflecting the statistical precision of the calibration samples and possible imperfections of the parametrization, contribute to the systematic uncertainty on the final results. The dimuon trigger and the selection criteria applied at the dimuon level could potentially introduce muon-pair correlations, making the dimuon detection efficiencies different from the product of the efficiencies of the two single muons. Detailed MC simulations show that such correlations are essentially independent of $\cos\vartheta$ and φ, in the phase space selected for the measurement. Residual effects are incorporated into the systematic uncertainty.

A fit to the dimuon mass distribution provides the fraction of background events, f_B, under each of the three Υ mass peaks, for a given definition of the signal region. The angular distributions of these background events are modeled as weighted sums of the distributions measured in the mass sidebands (defined with negligible signal contamination), with weights derived under the assumption that they change monotonically with dimuon mass. The background dimuons are subtracted on an event-by-event basis using the likelihood ratio $L_B/L_{(S+B)}$, where both likelihoods are functions of the variables $p_T, |y|, M, \cos\vartheta$, and φ. L_B is the likelihood of an event to be background, reflecting the background model, and $L_{(S+B)}$ is its likelihood to be either signal or background, reflecting the distribution of the measured events. A fraction f_B of events distributed according to the $(p_T, |y|, M, \cos\vartheta, \varphi)$ distribution of the background model is removed from the data sample.

The posterior probability distribution (PPD) for the average values of the Υ polarization parameters ($\vec{\lambda}$) inside a particular kinematic cell 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. The priors are assumed to be uniform in the full parameter space. Unlike most polarization analyses, we do not use simulated $(\cos\vartheta, \varphi)$ acceptance and efficiency maps, averaged over all events in the considered kinematic cell. Instead, the procedure exploits the efficiency measurement as a function of muon momenta, attributing to each event a probability dependent on the full event kinematics (not only $\cos\vartheta$ and φ) and on the values of the polarization parameters. The event probability is defined 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 $\epsilon(\vec{p}_1, \vec{p}_2)$ is the detection efficiency. The normalization factor $\mathcal{N}(\vec{\lambda})$ is calculated by integrating $W \cdot \epsilon$ over $\cos\vartheta$ and φ uniformly, using $(p_T, |y|, M)$ distributions determined from the background-subtracted data.

The background subtraction procedure is repeated 50 times to evaluate the statistical fluctuations associated with its random nature and the final PPD is obtained as the average of the 50 individual PPDs.

The analysis framework, including the effects of the detection efficiencies, has been tested with pseudo-experiments based on simulated samples. Each test involves 50 pseudo-experiments and evaluates a specific systematic uncertainty. The pseudo-samples are individually generated and reconstructed, leading to statistically independent determinations of the polarization parameters. The difference between the median of the 50 results and the injected polarization parameters provides the systematic uncertainty corresponding to the effect under study. The reliability of the method to extract the signal polarization is evaluated for several signal and background polarization scenarios. The influence of a possible residual bias from muon or dimuon efficiencies, stemming from the tag-and-probe measurement precision or from the efficiency parametrization, is evaluated by applying uncertainty-based changes to the efficiencies used in the extraction of the polarization parameters. The monotonicity hypothesis in the data-driven modeling of the background angular distribution under the Υ(nS) peaks has been tested by varying the signal region from $\pm 3\,\sigma$ to $\pm 1\,\sigma$ around the Υ(nS) masses (with corresponding

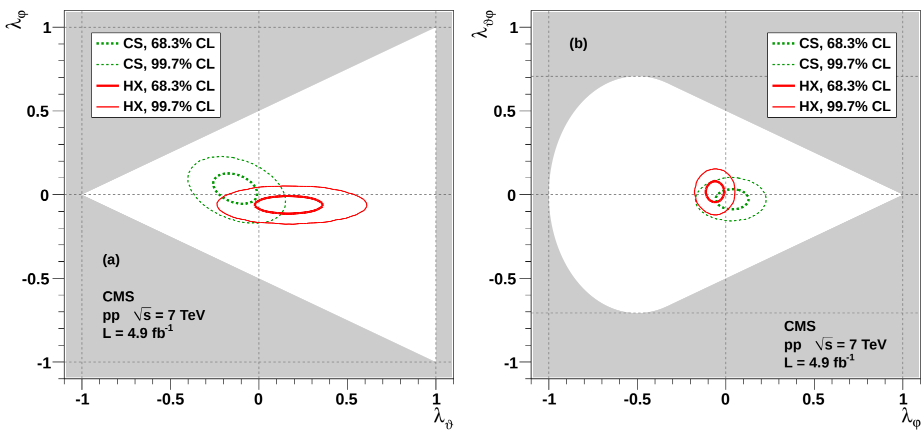

Figure 2: Two-dimensional projections of the PPD in the λ_φ vs. λ_ϑ (a) and $\lambda_{\vartheta\varphi}$ vs. λ_φ (b) planes, for $\Upsilon(1S)$ with $|y| < 0.6$ and $30 < p_T < 50$ GeV. The 68.3% and 99.7% CL contours are shown for the CS and HX frames. The shaded areas represent physically forbidden regions of parameter space [18].

corrections determined from a simple simulation of two-body decay kinematics). Despite significant changes in f_B (from 40% to 28% for the $\Upsilon(3S)$ at low p_T and $|y| < 0.6$, for instance), the results remain essentially identical for all three states. Larger variations are observed by modifying the relative weights of the low- and high-mass sidebands in the background model composition. A conservative range of hypotheses is considered, such as assuming 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. While there is no dominant source of systematic uncertainty in the $\Upsilon(1S)$ case, the total systematic uncertainty of the $\Upsilon(2S)$ and $\Upsilon(3S)$ states is dominated by the background model uncertainty, especially at low p_T. At high p_T, the statistical uncertainties dominate. For example, the statistical uncertainties in λ_ϑ(PX) at $|y| < 0.6$ for the $\Upsilon(1S)$ ($\Upsilon(3S)$) are of order 0.1 (0.2) at both low and high p_T; the corresponding systematic uncertainties have a similar magnitude at low p_T and are a factor of two (three) smaller at high p_T.

Each PPD is broadened by the effects of systematic uncertainties, which are included by convolution. One- and two-dimensional projections of each final PPD are calculated by numerical integration. The highest posterior probability in each one-dimensional projection is used to estimate the best value of the associated polarization parameter. Intervals $[\lambda_1, \lambda_2]$ corresponding to a given confidence level (CL), are calculated by identifying two regions of the parameter space, $[-\infty, \lambda_1]$ and $[\lambda_2, \infty]$, each containing $0.5 \cdot (1 - \mathrm{CL})$% of the one-dimensional projection of the PPD. Figure 2 shows two projections of the final PPD for the $\Upsilon(1S)$ at $|y| < 0.6$ and $30 < p_T < 50$ GeV, displaying the 68.3% and 99.7% CL contours for the CS and HX frames.

Figure 3 shows, for the rapidity range 0.0–0.6, one-dimensional profiles (68.3%, 95.5%, and 99.7% CL intervals) of the PPDs of the parameters λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$, for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states, in the HX frame. Similar values are obtained in the 0.6–1.2 rapidity range [25]. Figure 4 displays the corresponding results for the frame-invariant parameter $\tilde{\lambda}$, including also the CS and PX values. The results obtained in the three frames are in good agreement, as required in the absence of unaccounted for systematic effects. Complete tables of results for λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$, and $\tilde{\lambda}$, for the three Υ states and in the three frames considered in this analysis, are available in Ref. [25].

All the polarization parameters are compatible with zero or small values in the three polarization frames, excluding that a significant polarization could remain undetected because of

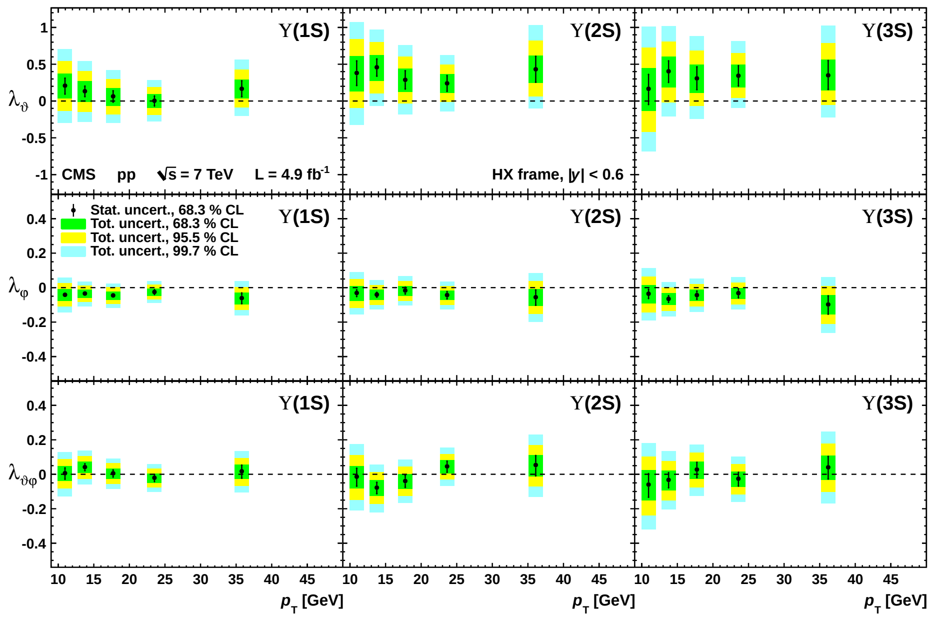

Figure 3: Values of the λ_ϑ (top), λ_φ (middle), and $\lambda_{\vartheta\varphi}$ (bottom) parameters for the Υ(1S) (left), Υ(2S) (middle), and Υ(3S) (right), in the HX frame, as a function of the Υ p_T for $|y| < 0.6$. The error bars indicate the 68.3% CL interval when neglecting the systematic uncertainties. The three bands represent the 68.3%, 95.5%, and 99.7% CL intervals of the total uncertainties. The points are placed at the average p_T of each bin.

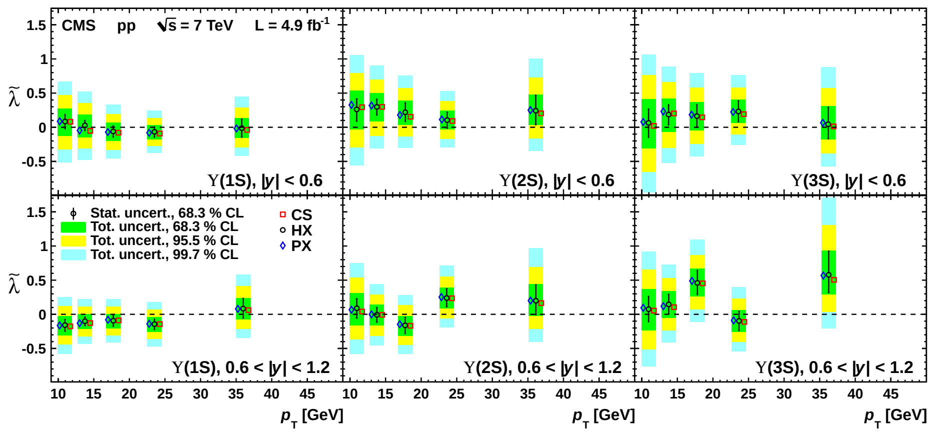

Figure 4: Values of $\tilde{\lambda}$ for the Υ(1S), Υ(2S), and Υ(3S) states (left to right), in the HX, CS, and PX frames, for the $|y| < 0.6$ (left) and $0.6 < |y| < 1.2$ (right) ranges. The bands and error bars have the same meaning as in the previous figure.

smearing effects induced by unfortunate frame choices. The indication that the Υ(nS) resonances are produced as an unpolarized mixture might be related to the fact that the measurements do not distinguish directly produced Υ mesons from those produced in the decays of heavier (P-wave) bottomonium states.

In summary, the polarizations of the Υ(nS) mesons produced in pp collisions at $\sqrt{s} = 7$ TeV have been determined as a function of the Υ p_T in two rapidity ranges and in three different polarization frames, using both frame-dependent and frame-independent parameters. The results exclude large transverse or longitudinal Υ(nS) polarizations, beyond the p_T and y ranges probed by previous experiments, especially for the Υ(3S) state, less affected by feed-down decays, and are in disagreement with theoretical expectations for high-energy hadron collisions [10, 26].

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47: Also at Ozyegin University, Istanbul, Turkey
48: Also at Kafkas University, Kars, Turkey
49: Also at Suleyman Demirel University, Isparta, Turkey
50: Also at Ege University, Izmir, Turkey
51: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
52: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
53: Also at Utah Valley University, Orem, USA
54: Now at University of Edinburgh, Scotland, Edinburgh, United Kingdom

55: Also at Institute for Nuclear Research, Moscow, Russia
56: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
57: Also at Argonne National Laboratory, Argonne, USA
58: Also at Erzincan University, Erzincan, Turkey
59: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
60: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
61: Also at Kyungpook National University, Daegu, Korea