Measurement of the (1S), (2S), and (3S) Polarizations in pp Collisions at s=7TeV

<table>
<thead>
<tr>
<th>Citation</th>
<th>Chatrchyan, S., V. Khachatryan, A. M. Sirunyan, et al. Measurement of the (1S), (2S), and (3S) Polarizations in Pp Collisions at Sqrt[s]=7TeV. Physical Review Letters 110(8), 2013. © 2013 CERN, for the CMS Collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevLett.110.081802">http://dx.doi.org/10.1103/PhysRevLett.110.081802</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Sun Dec 30 19:17:42 EST 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/78626">http://hdl.handle.net/1721.1/78626</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Creative Commons Attribution 3.0</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td><a href="http://creativecommons.org/licenses/by/3.0/">http://creativecommons.org/licenses/by/3.0/</a></td>
</tr>
</tbody>
</table>
Measurement of the $Y(1S)$, $Y(2S)$, and $Y(3S)$ Polarizations in $pp$ Collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan et al. (CMS Collaboration)
(Received 13 September 2012; published 20 February 2013)

The polarizations of the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons are measured in proton-proton collisions at $\sqrt{s} = 7$ TeV, using a data sample of $Y(nS) \rightarrow \mu^+ \mu^-$ decays collected by the CMS experiment, corresponding to an integrated luminosity of 4.9 fb$^{-1}$. The dimuon decay angular distributions are analyzed in three different polarization frames. The polarization parameters $\lambda_\phi$, $\lambda_\varphi$, and $\lambda_{\delta\varphi}$, as well as the frame-invariant quantity $\lambda$, are presented as a function of the $Y(nS)$ 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.

DOI: 10.1103/PhysRevLett.110.081802 PACS numbers: 13.20.Gd, 13.85.Qk, 13.88.+e

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 $J/\psi$ and $Y$ 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 $J/\psi$ [11]. The $Y$ satisfies the nonrelativistic approximation much better than the $J/\psi$, making the $Y$ 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 $(J^{PC} = 1^{-+})$ $Y$ states can be measured through the study of the angular distribution of the leptons produced in the $Y \rightarrow \mu^+ \mu^-$ decay [14],

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

where $\theta$ and $\varphi$ are the polar and azimuthal angles, respectively, of the $\mu^+$ 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, $\lambda = (\lambda_\varphi + 3\lambda_\theta)/(1 - \lambda_\varphi)$. This approach has already been followed in the $Y(nS)$ polarization analysis of CDF [12], and in some recent theory calculations [19].

This Letter presents the measurement of the polarizations of the $Y(nS)$ 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 $Y(1S)$, 94 000 $Y(2S)$, and 58 000 $Y(3S)$ 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 $Y$ momentum; the Collins-Soper (CS) frame [20], whose axis is the average of the two beam directions in the $Y$ 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 $8.5 < M < 11.5$ GeV, $|y| < 1.25$, $p_T > 5$ or 7 GeV (depending on the instantaneous luminosity), and vertex fit circles.Offline trigger confirmation, the combinatorial background from uncorrelated muons is reduced by requiring a dimuon correlation, making the dimuon detection efficiency of the two single muons. Detailed MC simulations show that such correlations are essentially independent of $p_T$ and $\eta$ bins. Their uncertainties, reflecting the statistical precision of the calibration samples and possible imperfections of the parameterization, 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 $\cos\theta$ and $\varphi$, 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 $Y$ 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 $p_T$, $|y|$, $M$, $\cos\theta$, and $\varphi$. $L_B$ 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 $(p_T, |y|, M, \cos\theta, \varphi)$ distribution of the background model is removed from the data sample. The posterior probability distribution (PPD) for the average values of the $Y$ polarization parameters ($\lambda$) inside a particular kinematic cell is then defined as a product over the remaining (“signal-like”) events $i$,

$$P(\lambda) = \prod_i \mathcal{E}(p_{1i}^\theta, p_{2i}^\theta),$$

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 ($\cos\theta$, $\varphi$) acceptance and efficiency maps, averaged over

**FIG. 1** (color online). Dimuon mass distributions in the $Y$ region for $|y| < 0.6$ (open squares) and $0.6 < |y| < 1.2$ (closed circles).
all events in the considered kinematic cell. Instead, the
procedure exploits the efficiency measurement as a func-
tion of muon momenta, attributing to each event a proba-
bility dependent on the full event kinematics (not only
$\cos \theta$ and $\varphi$) and on the values of the polarization param-
ters. The event probability is defined as

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

(3)

where $\epsilon(\vec{p}_1, \vec{p}_2)$ is the detection efficiency. The normali-
ization factor $\mathcal{N}(\lambda)$ is calculated by integrating $W \cdot \epsilon$ over
$\cos \theta$ and $\varphi$ 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 pseudoexperi-
ments based on simulated samples. Each test involves
50 pseudoexperiments and evaluates a specific systematic
uncertainty. The pseudosamples are individually generated
and reconstructed, leading to statistically independent
determinations of the polarization parameters. The differ-
ence 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 measure-
ment precision or from the efficiency parametrization, is
examined. An estimate of 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 $Y(1S)$ [$Y(3S)$] peak resembles exclu-
sively 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 system-
atic uncertainty in the $Y(1S)$ case, the total systematic
uncertainty of the $Y(2S)$ and $Y(3S)$ 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 $\lambda_\theta$ ($\lambda_\phi$) at $|y| < 0.6$ for the
$Y(1S)$ [$Y(3S)$] 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 two [three] times 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 para-
meter. Intervals $[\lambda_1, \lambda_2]$ corresponding to a given confi-
dence level (CL), are calculated by identifying two regions
of the parameter space, $[-\infty, \lambda_1]$ and $[\lambda_2, \infty]$, each con-
taining 0.5(1−CL)% of the one-dimensional projection of the
PPD. Figure 2 shows two projections of the final PPD
for the $Y(1S)$ at $|y| < 0.6$ and $30 < p_T < 50$ GeV, display-
ing the 68.3% and 99.7% CL contours for the CS and HX frames.

![FIG. 2 (color online). Two-dimensional projections of the PPD in the $\lambda_\phi$ vs $\lambda_\theta$ (a) and $\lambda_\phi$ vs $\lambda_\theta$ (b) planes, for $Y(1S)$ 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].](image-url)
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 $\lambda_{/C21}$, $\lambda_{/C21'}$, and $\lambda_{/C21''}$, for the $/C7(1S)$, $/C7(2S)$, and $/C7(3S)$ states, in the HX frame. Similar values are obtained in the 0.6–1.2 rapidity range (see the Supplemental Material [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 $\lambda_{/C21}$, $\lambda_{/C21'}$, $\lambda_{/C21''}$, and $\tilde{\lambda}$, for the three $/C7$ states and in the three frames considered in this analysis, are available in the Supplemental Material [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 smearing effects induced by unfortunate frame choices. The indication that the $/C7(nS)$ resonances are

![FIG. 3 (color online). Values of the $\lambda_{/C21}$ (top), $\lambda_{/C21'}$ (middle), and $\lambda_{/C21''}$ (bottom) parameters for the $/C7(1S)$ (left), $/C7(2S)$ (middle), and $/C7(3S)$ (right), in the HX frame, as a function of the $/C7p_T$ 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 $/C7p_T$ of each bin.](image)

![FIG. 4 (color online). Values of $\tilde{\lambda}$ for the $/C7(1S)$, $/C7(2S)$, and $/C7(3S)$ states (left to right), in the HX, CS, and PX frames, for the $|y| < 0.6$ (top) and $0.6 < |y| < 1.2$ (bottom) ranges. The bands and error bars have the same meaning as in the previous figure.](image)
produced as an unpolarized mixture might be related to the fact that the measurements do not distinguish directly produced Y mesons from those produced in the decays of heavier (P-wave) bottomonium states.

In summary, the polarizations of the $Y(nS)$ mesons produced in $pp$ collisions at $\sqrt{s}=7$ TeV have been determined as a function of the $Y$ $p_T$ 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 $Y(nS)$ polarizations, beyond the $p_T$ and $y$ ranges probed by previous experiments, especially for the $Y(3S)$ state, less affected by feeddown decays, and are in disagreement with theoretical expectations for high-energy hadron collisions [10,26].

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge sup-

K. Klapoetke,140 Y. Kubota,140 J. Mans,140 N. Pastika,140 R. Rusack,140 M. Sasseville,140 A. Singovsky,140
N. Tambe,140 J. Turkewitz,140 L. M. Cremalhi,141 R. Kroeger,141 L. Perera,141 R. Rahmat,141 D. A. Sanders,141
E. Avdeeva,142 K. Bloom,142 S. Bose,142 D. R. Claes,142 A. Dominguez,142 M. Eads,142 J. Keller,142 I. Kravchenko,142
J. Lazo-Flores,142 S. Malik,142 G. R. Snow,142 A. Godshall,143 I. Iashvili,143 S. Jain,143 A. Kharchilava,143
A. Kumar,143 S. Rappoccio,143 G. Alversion,144 E. Barberis,144 D. Baumgartel,144 M. Chasco,144 J. Haley,144
M. Velasco,145 S. Won,145 L. Antonelli,146 D. Berry,146 A. Brinkerhoff,146 K. M. Chan,146 M. Hildreth,146
C. Jessop,146 D. J. Karmgard,146 J. Kolb,146 K. Lannon,146 W. Luo,146 S. Lynch,146 N. Marinelli,146 D. M. Morse,146
T. Pearson,146 M. Planer,146 R. Ruchti,146 J. Slaunwhite,146 N. Valls,146 M. Wolf,146 B. Bylsma,147
L. S. Durkin,147 C. Hill,147 R. Hughes,147 K. Kotov,147 T. Y. Ling,147 D. Puigh,147 M. Rodenburg,147 C. Vuosalo,147
G. Williams,147 B. L. Winer,147 E. Berry,147 P. Elmer,147 V. Halyo,147 P. Hebdal,147 J. Hegeman,148 A. Hunt,148
A. Zuranski,148 E. Brownson,149 A. Lopez,149 H. Mendez,149 J. E. Ramirez Vargas,149 E. Alagoz,150 V. E. Barnes,150
D. Benedetti,150 G. Bolla,150 D. Bortoletto,150 M. De Mattia,150 A. Everett,150 Z. Hu,150 M. Jones,150 K. Oyubasi,150
I. Shipsey,150 D. Silvers,150 A. Svyatkovskiy,150 M. Vidal Marono,150 H. D. Yoo,150 J. Zablocki,150 Y. Zheng,150
L. Demortier,154 K. Goulianos,154 G. Lungu,154 S. Malik,154 C. Mesropian,154 S. Arora,155 A. Barker,155
J. P. Chou,155 C. Contreras-Campana,155 E. Contreras-Campana,155 D. Duggan,155 D. Ferencek,155 Y. Gershtein,155
R. Gray,155 E. Halkiadakis,155 D. Hidas,155 A. Lath,155 S. Panwalkar,155 M. Park,155 R. Patel,155 V. Rekovic,155
J. Robles,155 K. Rose,155 S. Salur,155 S. Schnetzer,155 C. Setz,155 S. Somalwar,155 R. Stone,155 S. Thomas,155
M. Walker,155 G. Cerizza,156 M. Hollingsworth,156 S. Spanier,156 Z. C. Yang,156 A. York,156 R. Eusebi,156
N. Akhurin,158 J. Damgov,158 C. Dragou,158 P. R. Duder,158 C. Jeong,158 K. Kostantinou,158 S. W. Lee,158
T. Libeiro,158 Y. Roh,158 I. Volobouev,158 A. Appel,158 A. G. Delannoy,159 C. Florez,159 S. Greene,159 A. Gurrola,159
W. Johns,159 P. Kurt,159 C. Maguire,159 A. Melo,159 M. Sharma,159 P. Sheldon,159 B. Snoch,159 S. Tuo,159
C. Kottachchi Kankanamge Don,161 P. Lamichhane,161 A. Sakharov,161 M. Anderson,162 D. Belknap,162
L. Borrello,162 D. Carlsmit,162 M. Cepeda,162 S. Dasu,162 E. Friis,162 L. Gray,162 K. S. Grogg,162 M. Grothe,162
R. Hall-Wilton,162 M. Herndon,162 A. Herve,162 P. Klabbers,162 J. Klukas,162 A. Lanaro,162 C. Lazaridis,162
R. Loveless,162 A. Mohapatra,162 I. Ojalvo,162 F. Palmonari,162 G. A. Pierro,162 I. Ross,162 S. Savin,162
W. H. Smith,162 and J. Swanson162

(CMS Collaboration)

1Yerevan Physics Institute, Yerevan, Armenia
2Institut für Hochenergiephysik der OeAW, Wien, Austria
3National Centre for Particle and High Energy Physics, Minsk, Belarus
4Universiteit Antwerpen, Antwerpen, Belgium
5Vrije Universiteit Brussel, Brussel, Belgium
6Université Libre de Bruxelles, Bruxelles, Belgium
7Ghent University, Gent, Belgium
8Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9Université de Mons, Mons, Belgium
10Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
11Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

081802-11

PRL 110, 081802 (2013) PHYSICAL REVIEW LETTERS week ending 22 FEBRUARY 2013
114 The University of Alabama, Tuscaloosa, Alabama, USA  
115 Boston University, Boston, Massachusetts, USA  
116 Brown University, Providence, Rhode Island, USA  
117 University of California, Davis, Davis, California, USA  
118 University of California, Los Angeles, Los Angeles, California, USA  
119 University of California, Riverside, Riverside, California, USA  
120 University of California, San Diego, La Jolla, California, USA  
121 University of California, Santa Barbara, Santa Barbara, California, USA  
122 California Institute of Technology, Pasadena, California, USA  
123 Carnegie Mellon University, Pittsburgh, Pennsylvania, USA  
124 University of Colorado at Boulder, Boulder, Colorado, USA  
125 Cornell University, Ithaca, New York, USA  
126 Fairfield University, Fairfield, Connecticut, USA  
127 Fermi National Accelerator Laboratory, Batavia, Illinois, USA  
128 University of Florida, Gainesville, Florida, USA  
129 Florida International University, Miami, Florida, USA  
130 Florida State University, Tallahassee, Florida, USA  
131 Florida Institute of Technology, Melbourne, Florida, USA  
132 University of Illinois at Chicago (UIC), Chicago, Illinois, USA  
133 The University of Iowa, Iowa City, Iowa, USA  
134 Johns Hopkins University, Baltimore, Maryland, USA  
135 The University of Kansas, Lawrence, Kansas, USA  
136 Kansas State University, Manhattan, Kansas, USA  
137 Lawrence Livermore National Laboratory, Livermore, California, USA  
138 University of Maryland, College Park, Maryland, USA  
139 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA  
140 University of Minnesota, Minneapolis, Minnesota, USA  
141 University of Mississippi, Oxford, Mississippi, USA  
142 University of Nebraska-Lincoln, Lincoln, Nebraska, USA  
143 State University of New York at Buffalo, Buffalo, New York, USA  
144 Northeastern University, Boston, Massachusetts, USA  
145 Northwestern University, Evanston, Illinois, USA  
146 University of Notre Dame, Notre Dame, Indiana, USA  
147 The Ohio State University, Columbus, Ohio, USA  
148 Princeton University, Princeton, New Jersey, USA  
149 University of Puerto Rico, Mayaguez, Puerto Rico, USA  
150 Purdue University, West Lafayette, Indiana, USA  
151 Purdue University Calumet, Hammond, Indiana, USA  
152 Rice University, Houston, Texas, USA  
153 University of Rochester, Rochester, New York, USA  
154 The Rockefeller University, New York, New York, USA  
155 Rutgers, the State University of New Jersey, Piscataway, New Jersey, USA  
156 University of Tennessee, Knoxville, Tennessee, USA  
157 Texas A&M University, College Station, Texas, USA  
158 Texas Tech University, Lubbock, Texas, USA  
159 Vanderbilt University, Nashville, Tennessee, USA  
160 University of Virginia, Charlottesville, Virginia, USA  
161 Wayne State University, Detroit, Michigan, USA  
162 University of Wisconsin, Madison, Wisconsin, USA  

a Deceased.  
Also at Vienna University of Technology, Vienna, Austria.  
Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.  
Also at Universidade Federal do ABC, Santo Andre, Brazil.  
Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.  
Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.  
Also at Suez Canal University, Suez, Egypt.  
Also at Zewail City of Science and Technology, Zewail, Egypt.  
Also at Cairo University, Cairo, Egypt.