The double-differential cross sections of promptly produced $J/\psi$ and $\psi(2S)$ mesons are measured in $pp$ collisions at $\sqrt{s} = 7$ TeV, as a function of transverse momentum $p_T$ and absolute rapidity $|y|$. The analysis uses $J/\psi$ and $\psi(2S)$ dimuon samples collected by the CMS experiment, corresponding to integrated luminosities of 4.55 and 4.90 fb$^{-1}$, respectively. The results are based on a two-dimensional analysis of the dimuon invariant mass and decay length, and extend to $p_T = 120$ and 100 GeV for the $J/\psi$ and $\psi(2S)$, respectively, when integrated over the interval $|y| < 1.2$. The ratio of the $\psi(2S)$ to $J/\psi$ cross sections is also reported for $|y| < 1.2$, over the range $10 < p_T < 100$ GeV. These are the highest $p_T$ values for which the cross sections and ratio have been measured.

DOI: 10.1103/PhysRevLett.114.191802

PACS numbers: 13.20.Gd, 13.85.Qk, 13.88.+e

Studies of heavy-quarkonium production are of central importance for an improved understanding of nonperturbative quantum chromodynamics (QCD) [1]. The nonrelativistic QCD (NRQCD) effective-field-theory framework [2], arguably the best formalism at this time, factorizes high-$p_T$ quarkonium production in short-distance and long-distance scales. First, a heavy quark-antiquark pair, $Q \bar{Q}$, is produced in a Fock state $2S+1L^{|J\rangle}$, with spin $S$, orbital angular momentum $L$, and total angular momentum $J$ that are either identical to (color singlet, $a = 1$) or different from (color octet, $a = 8$) those of the corresponding quarkonium state. The $Q \bar{Q}$ cross sections are determined by short-distance coefficients (SDCs), kinematic-dependent functions calculable perturbatively as expansions in the strong-coupling constant $\alpha_s$. Then this “preresonant” $Q \bar{Q}$ pair binds into the physically observable quarkonium through a nonperturbative evolution that may change $L$ and $S$, with bound-state formation probabilities proportional to long-distance matrix elements (LDMEs). The LDMEs are conjectured to be constant (i.e., independent of the $Q \bar{Q}$ momentum) and universal (i.e., process independent). The color-octet terms are expected to long-distance matrix elements (LDMEs). The LDMEs crucially depend on the minimum $p_T$ of the fitted measurements [6], because the octet LDMEs have different $p_T$ dependences. Fits including low-$p_T$ cross sections lead to the conclusion that, at high $p_T$, quarkonium production should be dominated by transversely polarized octet terms. This prediction is in stark contradiction with the unpolarized production seen by the CDF [7,8] and CMS [9,10] experiments, an observation known as the “quarkonium polarization puzzle.” As shown in Ref. [6], the puzzle is seemingly solved by restricting the NRQCD global fits to high-$p_T$ quarkonia, indicating that the presently available fixed-order calculations provide SDCs that are unable to reproduce reality at lower $p_T$ values or that NRQCD factorization only holds for $p_T$ values much larger than the quarkonium mass. The polarization measurements add a crucial dimension to the global fits because the various channels have remarkably distinct polarization properties: in the helicity frame, $^3S_1^1$ is longitudinally polarized, $^1S_0^8$ is unpolarized, $^3S_1^8$ is transversely polarized, and $^3P_J^8$ has a polarization that changes significantly with $p_T$. Bottomonium and prompt charmonium polarizations reaching or exceeding $p_T = 50$ GeV were measured by CMS [9,10], using a very robust analysis framework [11,12], on the basis of event samples collected in 2011. Instead, the differential charmonium cross sections published by CMS [13] are based on data collected in 2010 and have a much lower $p_T$ reach. Measurements of prompt charmonium cross sections extending well beyond $p_T = 50$ GeV will trigger improved NRQCD global fits, restricted to a kinematic domain where the factorization formalism is...
unquestioned, and will provide more accurate and reliable LDMEs.

This Letter presents measurements of the double-differential cross sections of $J/\psi$ and $\psi(2S)$ mesons promptly produced in $pp$ collisions at a center-of-mass energy of 7 TeV, based on dimuon event samples collected by CMS in 2011. They complement other prompt charmonium cross sections measured at the LHC, by ATLAS [14,15], LHCb [16,17], and ALICE [18]. The analysis is made in four bins of absolute rapidity ($|y| < 0.3$, $0.3 < |y| < 0.6$, $0.6 < |y| < 0.9$, and $0.9 < |y| < 1.2$) and in the $p_T$ ranges 10–95 GeV for the $J/\psi$ and 10–75 GeV for the $\psi(2S)$. A rapidity-integrated result in the range $|y| < 1.2$ is also provided, extending the $p_T$ reach to 120 GeV for the $J/\psi$ and 100 GeV for the $\psi(2S)$. The corresponding $\psi(2S)$ over $J/\psi$ cross section ratios are also reported. The dimuon invariant mass distribution is used to separate the $J/\psi$ and $\psi(2S)$ signals from other processes, mostly pairs of uncorrelated muons, while the dimuon decay length is used to separate the non-prompt charmonia, coming from decays of $b$ hadrons, from the prompt component. Feed-down from decays of heavier charmonium states, approximately 33% of the prompt $J/\psi$ cross section [19], is not distinguished from the directly produced charmonia.

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 three kinds of gas-ionization detectors: drift tubes, cathode strip chambers, and resistive-plate chambers. The main subdetectors used in this analysis are the silicon tracker and the CMS detector, 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. [20].

The events were collected using a two-level trigger system. The first level, made of custom hardware processors, uses data from the muon system to select events with two muon candidates. The high-level trigger, adding information from the silicon tracker, reduces the rate of stored events by requiring an opposite-sign muon pair of invariant mass $2.8 < M < 3.35$ GeV, $p_T > 9.9$ GeV, and $|y| < 1.25$ for the $J/\psi$ trigger, and $3.35 < M < 4.05$ GeV and $p_T > 6.9$ GeV for the $\psi(2S)$ trigger. No $p_T$ requirement is imposed on the single muons at trigger level. Both triggers require a dimuon vertex fit $\chi^2$ probability greater than 0.5% and a distance of closest approach between the two muons less than 5 mm. Events where the muons bend towards each other in the magnetic field are rejected to lower the trigger rate while retaining the highest-quality dimuons. The $J/\psi$ and $\psi(2S)$ analyses are conducted independently, using event samples separated at the trigger level. The $\psi(2S)$ sample corresponds to an integrated luminosity of 4.90 fb$^{-1}$, while the $J/\psi$ sample has a reduced value, 4.55 fb$^{-1}$, because the $p_T$ threshold of the $J/\psi$ trigger was raised to 12.9 GeV in a fraction of the data-taking period; the integrated luminosities have an uncertainty of 2.2% [21].

The muon tracks are required to have hits in at least eleven tracker layers, with at least two 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 ($Q^2$ per degree of freedom smaller than 1.8) and point to the interaction region. The selected muons must also match in pseudorapidity and azimuthal angle with the muon objects responsible for triggering the event. The analysis is restricted to muons produced within a fiducial phase-space window where the muon detection efficiencies are accurately measured: $p_T > 4.5$, 3.5, and 3.0 GeV for the regions $|\eta| < 1.2$, $1.2 < |\eta| < 1.4$, and $1.4 < |\eta| < 1.6$, respectively. The combinatorial dimuon background is reduced by requiring a dimuon vertex fit $\chi^2$ probability larger than 1%. Applying the event selection criteria, the combined yields of prompt and nonprompt charmonia in the range $|y| < 1.2$ are 5.45 M for the $J/\psi$ and 266 k for the $\psi(2S)$. The prompt charmonia are separated from those resulting from decays of $b$ hadrons through the use of the dimuon pseudo-proper-decay-length [22], $L_{xy} = L_{xy}/M/p_T$, where $L_{xy}$ is the transverse decay length in the laboratory frame, measured after removing the two muon tracks from the calculation of the primary vertex position. For events with multiple collision vertices, $L_{xy}$ is calculated with respect to the vertex closest to the direction of the dimuon momentum, extrapolated towards the beam line.

For each $|(y), (p_T)|$ bin, the prompt charmonium yields are evaluated through an extended unbinned maximum-likelihood fit to the two-dimensional $(M, \ell)$ event distribution. In the mass dimension, the shape of each signal peak is represented by a Crystal Ball (CB) function [23], with free mean ($\mu_{CB}$) and width ($\sigma_{CB}$) parameters. Given the strong correlation between the two CB tail parameters, $\alpha_{CB}$ and $n_{CB}$, they are fixed to values evaluated from fits to event samples integrated in broader $p_T$ ranges. A single CB function provides a good description of the signal mass peaks, given that the dimuon mass distributions are studied in narrow $(|y|, p_T)$ bins, within which the dimuon invariant mass resolution has a negligible variation. The mass distribution of the underlying continuum background is described by an exponential function. Concerning the pseudo-proper-decay-length variable, the prompt signal component is modeled by a resolution function, which exploits the per-event uncertainty information provided by the vertex reconstruction algorithm, while the nonprompt charmonium term is modeled by an exponential function convolved with the resolution function. The continuum background component is represented by a sum of prompt
and nonprompt empirical forms. The distributions are well described with a relatively small number of free parameters.

Figure 1 shows the $J/\psi$ and $\psi(2S)$ dimuon invariant mass and pseudo-proper-decay-length projections for two representative $(|\eta|, p_T)$ bins. The decay length projections are shown for events with dimuon invariant mass within $\pm 3\sigma_{CB}$ of the pole mass. In the highest $p_T$ bins, where the number of dimuons is relatively small, stable results are obtained by fixing $m_{CB}$ and the slope of the exponential-like function describing the nonprompt combinatorial background to values extrapolated from the trend found from the lower-$p_T$ bins. The systematic uncertainties in the signal yields are evaluated by repeating the fit with different functional forms, varying the values of the fixed parameters, and allowing for more free parameters in the fit. The fit results are robust with respect to changes in the procedure; the corresponding systematic uncertainties are negligible at low $p_T$ and increase to $\approx 2\%$ for the $J/\psi$ and $\approx 6\%$ for the $\psi(2S)$ in the highest $p_T$ bins.

The single-muon detection efficiencies $\epsilon_{\mu}$ are measured with a “tag-and-probe” (T&P) technique [24], using event samples collected with triggers specifically designed for this purpose, including a sample enriched in dimuons from $J/\psi$ decays where a muon is combined with another track and the pair is required to have an invariant mass within the range 2.8–3.4 GeV. The procedure was validated in the phase-space window of the analysis with detailed Monte Carlo (MC) simulation studies. The measured efficiencies are parametrized as a function of muon $p_T$, in eight bins of muon $|\eta|$. Their uncertainties, reflecting the statistical precision of the T&P samples and possible imperfections of the parametrization, are $\approx 2\%–3\%$. The efficiency of the dimuon vertex fit $\chi^2$ probability requirement is also measured with the T&P approach, using a sample of events collected with a dedicated (prescaled) trigger. It is around 95%–97%, improving with increasing $p_T$, with a 2% systematic uncertainty. At high $p_T$, when the two muons might be emitted relatively close to each other, the efficiency of the dimuon trigger $\epsilon_{\mu\mu}$ is smaller than the product of the two single-muon efficiencies $\epsilon_{\mu} \epsilon_{\mu} \rho$. The correction factor $\rho$ is evaluated with MC simulations, validated from data collected with single-muon triggers. For $p_T < 35$ GeV, $\rho$ is consistent with being unity, within a systematic uncertainty estimated as

![Graphs showing dimuon invariant mass and pseudo-proper-decay-length projections for $J/\psi$ and $\psi(2S)$ events.](image-url)
The two other parameters characterizing the dimuon integrated luminosity and the widths of the event basis for efficiencies and acceptance, by the integration of the branching fraction, are obtained by dividing the fitted numerical values, including the relative statistical and systematic uncertainties, are reported for both charmonia, except in the $0.9 < |y| < 1.2$ bin, where the uncertainty increases to 4.3% for the $J/\psi$ if $p_T < 12$ GeV, and to 2.7% for the $\psi(2S)$ if $p_T < 11$ GeV. For $p_T > 35$ GeV, $\rho$ decreases approximately linearly with $p_T$, reaching 60%–70% for $p_T \approx 85$ GeV, with systematic uncertainties evaluated by comparing the MC simulation results with estimations made using data collected with single-muon triggers: 5% up to $p_T = 50$ (55) GeV for the $J/\psi$ ($\psi(2S)$) and 10% for higher $p_T$. The total dimuon detection efficiency increases from $\epsilon_{\mu\mu} \approx 78\%$ at $p_T = 15$ GeV to $\approx 85\%$ at 30 GeV, and then decreases to $\approx 65\%$ at 80 GeV.

To obtain the charmonium cross sections in each $|y|$, $p_T$ bin without any restrictions on the kinematic variables of the two muons, we correct for the corresponding dimuon acceptance, defined as the fraction of dimuon decays having both muons emitted within the single-muon fiducial phase space. These acceptances are calculated using a detailed MC simulation of the CMS experiment. Charmonia are generated using a flat rapidity distribution and $p_T$ distributions based on previous measurements [13]; using flat $p_T$ distributions leads to negligible changes. The particles are decayed by EVTGEN [25] interfaced to PYTHIA 6.4 [26], while PHOTOS [27] is used to simulate final-state radiation. The fractions of $J/\psi$ and $\psi(2S)$ dimuon events in a given $|y|$, $p_T$ bin with both muons surviving the fiducial selections depend on the decay kinematics and, in particular, on the polarization of the mother particle. Acceptances are calculated using polarization scenarios corresponding to different values of the polar anisotropy parameter in the helicity frame, $\lambda_H^H$: 0 (unpolarized), +1 (transverse), and −1 (longitudinal). A fourth scenario, corresponding to $\lambda_H^H = +0.10$ for the $J/\psi$ and +0.03 for the $\psi(2S)$, reflects the results published by CMS [10]. The two other parameters characterizing the dimuon angular distributions [28], $\lambda_\rho$ and $\lambda_\rho_m$, have been measured to be essentially zero [10] and have a negligible influence on the acceptance. The acceptances are essentially identical for the two charmonia and are almost rapidity independent for $|y| < 1.2$. The two-dimensional acceptance maps are calculated with large MC simulation samples, so that statistical fluctuations are small, and in narrow $|y|$ bins, so that variations within the bins can be neglected. Since the efficiencies and acceptances are evaluated for events where the two muons bend away from each other, a factor of 2 is applied to obtain the final cross sections.

The double-differential cross sections of promptly produced $J/\psi$ and $\psi(2S)$ in the dimuon channel, $d^2\sigma/dp_T dy$, where $\mathcal{B}$ is the $J/\psi$ or $\psi(2S)$ dimuon branching fraction, are obtained by dividing the fitted prompt-signal yields, already corrected on an event-by-event basis for efficiencies and acceptance, by the integrated luminosity and the widths of the $p_T$ and $|y|$ bins. The numerical values, including the relative statistical and systematic uncertainties, are reported for both charmonia, five rapidity intervals, and four polarization scenarios in Tables 1–4 of the Supplemental Material [29]. Figure 2 shows the results obtained in the unpolarized scenario. With respect to the $|y| < 0.3$ bin, the cross sections drop by $\approx 5\%$ for $0.6 < |y| < 0.9$ and $\approx 15\%$ for $0.9 < |y| < 1.2$. Measuring the charmonium production cross sections in the broader rapidity range $|y| < 1.2$ has the advantage that the increased statistical accuracy allows the measurement to be extended to higher-$p_T$ values, where comparisons with theoretical calculations are particularly informative. Figure 3 compares the rapidity-integrated (unpolarized) cross sections, after rescaling with the branching fraction $\mathcal{B}$ of the dimuon decay channels [30], with results reported by ATLAS [14,15]. The curve represents a fit of the $J/\psi$ cross section measured in this analysis to a power-law function [31]. The band labeled FKLSW represents the result of a global fit [6] comparing SDCs calculated at NLO [3] with $\psi(2S)$ cross sections and polarizations previously reported by CMS [10,13] and LHCb [17]. According to that fit, $\psi(2S)$ mesons are produced predominantly unpolarized. At high $p_T$, the values reported in this Letter tend to be higher than the band, which is essentially determined from results for $p_T < 30$ GeV.

The ratio of the $\psi(2S)$ to $J/\psi$ differential cross sections is also measured in the $|y| < 1.2$ range, recomputing the $J/\psi$ values in the $p_T$ bins of the $\psi(2S)$ analysis. The measured values are reported in Table 5 of the Supplemental Material [29]. The corrections owing to the integrated luminosity, efficiencies, and acceptances cancel to a large extent in the measurement of the ratio. The total systematic uncertainty, dominated by the $\rho$ correction for $p_T > 30$ GeV and by the acceptance and...
efficiency corrections for $p_T < 20$ GeV, does not exceed 3%, except for $p_T > 75$ GeV, where it reaches 5%. Larger event samples are needed to clarify the trend of the ratio for $p_T$ above $\approx 35$ GeV.

In summary, the double-differential cross sections of the $J/\psi$ and $\psi(2S)$ mesons promptly produced in $p p$ collisions at $\sqrt{s} = 7$ TeV have been measured as a function of $p_T$ in four $|y|$ bins, as well as integrated over the $|y| < 1.2$ range, extending up to or beyond $p_T = 100$ GeV. New global fits of cross sections and polarizations, including these high-$p_T$ measurements, will probe the theoretical calculations in a kinematical region where NRQCD factorization is believed to be most reliable. The new data should also provide input to stringent tests of recent theory developments, such as those described in Refs. [32–34].

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

[1] N. Brambilla et al., Heavy quarkonium: progress, puzzles, and opportunities, Eur. Phys. J. C 71, 1534 (2011).
[2] G. T. Bodwin, E. Braaten, and G. P. Lepage, Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium, Phys. Rev. D 51, 1125 (1995).
[3] M. Butenschoen and B. A. Kniehl, $J/\psi$ Polarization at Tevatron and the LHC: Nonrelativistic-QCD Factorization at the Crossroads, Phys. Rev. Lett. 108, 172002 (2012).
[4] B. Gong, L.-P. Wan, J.-X. Wang, and H.-F. Zhang, Polarization for Prompt $J/\psi$, $\psi(2S)$ Production at the Tevatron and LHC, Phys. Rev. Lett. 110, 042002 (2013).
[5] K.-T. Chao, Y.-Q. Ma, H.-S. Shao, K. Wang, and Y.-J. Zhang, $J/\psi$ Polarization at Hadron Colliders in Nonrelativistic QCD, Phys. Rev. Lett. 108, 242004 (2012).
[6] P. Faccioli, V. Knünz, C. Lourenço, J. Seixas, and H. Wöhri, Quarkonium production in the LHC era: a polarized perspective, Phys. Lett. B 736, 98 (2014).
[7] A. Abulencia et al. (CDF Collaboration), Polarization of $J/\psi$ and $\psi(2S)$ Mesons Produced in $p \bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 99, 132001 (2007).
[8] T. Aaltonen et al. (CDF Collaboration), Measurements of Angular Distributions of Muons from $\Upsilon$ Decays in $p \bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 108, 151802 (2012).
[9] CMS Collaboration, Measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ Polarizations in $p p$ Collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. Lett. 110, 081802 (2013).
[10] CMS Collaboration, Measurement of the prompt $J/\psi$ and $\psi(2S)$ polarizations in $pp$ collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B 727, 381 (2013).
[11] P. Faccioli, C. Lourenço, and J. Seixas, Rotation-Invariant Relations in Vector Meson Decays into Fermion Pairs, Phys. Rev. Lett. 105, 061601 (2010).
[12] P. Faccioli, C. Lourenço, and J. Seixas, New approach to quarkonium polarization studies, Phys. Rev. D 81, 111502 (R) (2010).

[13] CMS Collaboration, $J/\psi$ and $\psi(2S)$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 02 (2012) 011.

[14] ATLAS Collaboration, Measurement of the differential cross-sections of inclusive, prompt and non-prompt $J/\psi$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV, Nucl. Phys. B850, 387 (2011).

[15] ATLAS Collaboration, Measurement of the production cross-section of $\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ in $pp$ collisions at $\sqrt{s} = 7$ TeV at ATLAS, J. High Energy Phys. 09, (2014) 079.

[16] LHCb Collaboration, Measurement of $J/\psi$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C 71, 1645 (2011).

[17] LHCb Collaboration, Measurement of $\psi(2S)$ meson production in $pp$ collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C 72, 2100 (2012).

[18] ALICE Collaboration, Measurement of prompt $J/\psi$ and beauty hadron production cross sections at mid-rapidity in $pp$ collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 11 (2012) 065.

[19] P. Faccioli, C. Lourenço, J. Seixas, and H. Wohri, Study of $\psi'$ and $\chi_c$ decays as feed-down sources of $J/\psi$ hadroproduction, J. High Energy Phys. 10, (2008) 004.

[20] CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3, S08004 (2008).

[21] CMS Collaboration, Absolute Calibration of the Luminosity Measurement at CMS: Winter 2012 Update, CMS Physics Analysis Summary Report No. CMS-PAS-SMP-12-008, 2012.

[22] CMS Collaboration, Prompt and non-prompt $J/\psi$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C 71, 1575 (2011).

[23] M. J. Oreglia, Ph.D. thesis, Stanford University, 1980, SLAC-R-236.

[24] CMS Collaboration, Measurements of inclusive $W$ and $Z$ cross sections in $pp$ collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 01 (2011) 080.

[25] D. J. Lange, The EvTGen particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A 462, 152 (2001).

[26] T. Sjostrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026.

[27] E. Barberio and Z. Was, PHOTOS—a universal Monte Carlo for QED radiative corrections: version 2.0, Comput. Phys. Commun. 79, 291 (1994).

[28] P. Faccioli, C. Lourenço, J. Seixas, and H. Wohri, Towards the experimental clarification of quarkonium polarization, Eur. Phys. J. C 69, 657 (2010).

[29] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.114.191802 for tables with detailed results.

[30] K. A. Olive et al. (Particle Data Group), Review of Particle Physics, Chin. Phys. C 38, 090001 (2014).

[31] I. Abt et al. (HERA-B), A measurement of the $\psi' \to J/\psi$ production ratio in 920 GeV proton-nucleus interactions, Eur. Phys. J. C 49, 545 (2007).

[32] Z.-B. Kang, J.-W. Qiu, and G. Sterman, Heavy Quarkonium Production and Polarization, Phys. Rev. Lett. 108, 102002 (2012).

[33] Z.-B. Kang, Y.-Q. Ma, J.-W. Qiu, and G. Sterman, Heavy quarkonium production at collider energies: Factorization and evolution, Phys. Rev. D 90, 034006 (2014).

[34] G.T. Bodwin, H. Sok Chung, U.-R. Kim, and J. Lee, Fragmentation Contributions to $J/\psi$ Production at the Tevatron and the LHC, Phys. Rev. Lett. 113, 022001 (2014).
Università del Piemonte Orientale (Novara), Torino, Italy
INFN Sezione di Trieste, Trieste, Italy
Università di Trieste, Trieste, Italy
Kangwon National University, Chuncheon, Korea
Kyungpook National University, Daegu, Korea
Chonbuk National University, Jeonju, Korea
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Korea University, Seoul, Korea
Seoul National University, Seoul, Korea
University of Seoul, Seoul, Korea
Sungkyunkwan University, Suwon, Korea
Vilnius University, Vilnius, Lithuania
National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Universidad Iberoamericana, Mexico City, Mexico
Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
University of Auckland, Auckland, New Zealand
University of Canterbury, Christchurch, New Zealand
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
National Centre for Nuclear Research, Swierk, Poland
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
Joint Institute for Nuclear Research, Dubna, Russia
Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
P.N. Lebedev Physical Institute, Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
Universidad Autónoma de Madrid, Madrid, Spain
Universidad de Oviedo, Oviedo, Spain
Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
CERN, European Organization for Nuclear Research, Geneva, Switzerland
Paul Scherrer Institut, Villigen, Switzerland
Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
Universität Zürich, Zurich, Switzerland
National Central University, Chung-Li, Taiwan
National Taiwan University (NTU), Taipei, Taiwan
Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
Cukurova University, Adana, Turkey
Middle East Technical University, Physics Department, Ankara, Turkey
Bogazici University, Istanbul, Turkey
Istanbul Technical University, Istanbul, Turkey
National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
University of Bristol, Bristol, United Kingdom
Rutherford Appleton Laboratory, Didcot, United Kingdom
Imperial College, London, United Kingdom
Brunel University, Uxbridge, United Kingdom
Baylor University, Waco, Texas 76798, USA
The University of Alabama, Tuscaloosa, Alabama 35487, USA
Boston University, Boston, Massachusetts 02215, USA
Brown University, Providence, Rhode Island 02912, USA
University of California, Davis, Davis, California 95616, USA
University of California, Los Angeles, California 90095, USA
University of California, Riverside, Riverside, California 92521, USA
University of California, San Diego, La Jolla, California 92093, USA
University of California, Santa Barbara, Santa Barbara, California 93106, USA
Deceased.

Also at Vienna University of Technology, Vienna, Austria.

Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

Also at Universidade Estadual de Campinas, Campinas, Brazil.

Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

Also at Université Libre de Bruxelles, Bruxelles, Belgium.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

Also at Suez University, Suez, Egypt.

Also at Cairo University, Cairo, Egypt.

Also at Fayoum University, El-Fayoum, Egypt.

Also at British University in Egypt, Cairo, Egypt.

Also at Ain Shams University, Cairo, Egypt.

Also at Université de Haute Alsace Mulhouse, Cottbus, Germany.

Also at Brandenburg University of Technology, Cottbus, Germany.
