PROCEEDINGS OF SCIENCE

Measurements of Quarkonium Production and Polarization at CMS

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Studies of quarkonium production and polarization play an important role in understanding QCD. CMS has recently measured the Υ(nS) (n=1,2,3) production cross sections and polarizations, as well as the prompt ψ(nS) (n=1,2) polarizations, using a dimuon sample collected in proton-proton collisions in 2011 at $\sqrt{s} = 7$ TeV. The differential cross sections of the Υ(nS) states are presented as a function of dimuon transverse momentum, covering a wide range of p_{T} (10–100 GeV). All three states show a similar behaviour and display a change of shape from an exponential to a power-law at $p_{\mathrm{T}} \approx 20$ GeV. The polarizations of the Υ(nS) and ψ(nS) states are determined in bins of dimuon transverse momentum and rapidity, significantly extending the p_{T} and rapidity ranges probed by previous experiments. The experimental measurements are in disagreement with current theoretical predictions.

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1. Introduction

Even after decades of experimental and theoretical research, quarkonium production is still not satisfactorily understood [1]. So far, no theory has been able to simultaneously describe quarkonium production and polarization. The Next-to-Leading Order (NLO) Non Relativistic Quantum ChromoDynamics (NRQCD), which includes color octet production, describes the production cross section of the J/ψ [2] but fails to explain the polarization. The J/ψ is predicted to be transversely polarized with respect to the momentum direction of the quarkonium state in the laboratory frame [3]. The CDF experiment, however, has measured the J/ψ polarization to be slightly longitudinal [4].

In the following sections, the latest CMS results on the Υ(nS) cross sections as well as on the Υ(nS) and ψ(nS) polarizations are presented. All measurements are based on a dimuon sample collected in proton-proton collisions at $\sqrt{s} = 7$ TeV, in 2011, corresponding to a total integrated luminosity of 4.9 fb^{-1}.

2. Υ(nS) Cross Section Measurement

The measurement of the differential cross section selects events with dimuon rapidity $|y| < 0.6$ and transverse momentum, p_{T}, between 10 and 100 GeV. The Υ(nS) differential cross section $\frac{d\sigma}{dp_{\mathrm{T}}}$ times dimuon branching ratio $\mathscr{B}$, integrated over $|y| < 0.6$, is calculated as

$$\left.\frac{d\sigma(pp \to \Upsilon(nS))}{dp_{\mathrm{T}}}\right|_{y<0.6} \times \mathscr{B}(\Upsilon(nS) \to \mu^+\mu^-) = \frac{N^{fit}_{\Upsilon(nS)}(p_{\mathrm{T}})}{L_{int} \cdot \Delta p_{\mathrm{T}} \cdot \varepsilon(p_{\mathrm{T}}) \cdot \mathscr{A}(p_{\mathrm{T}})}, \qquad (2.1)$$

where $N^{fit}_{\Upsilon(nS)}(p_{\mathrm{T}})$ is the number of Υ(nS) events in a given p_{T} bin of width Δp_{T}, L_{int} denotes the integrated luminosity, $\varepsilon(p_{\mathrm{T}})$ represents the efficiency of trigger, reconstruction and analysis selections, and $\mathscr{A}(p_{\mathrm{T}})$ the acceptance.

The acceptance is the polarization-weighted fraction of Υ's decaying into two muons, where the muons satisfy the kinematic requirements, to the total of weighted events in a given p_{T} bin. The calculation is done using Monte Carlo (MC) simulation and the Υ(nS) polarization measurements previously published by CMS [5].

Figure 1 (left) shows the p_{T} differential cross section times the branching ratio for the three Υ states. All states display a similar behaviour. Figure 1 (right) exhibits a fit to the cross section for the Υ(1S) state. It is clearly visible that the shape changes from an exponential to a power-law at $p_{\mathrm{T}} \approx 20$ GeV. This suggests a change in the nature of the production mechanism.

More details concerning the Υ(nS) cross section measurements can be found in Ref. [6].

3. Quarkonium Polarization

The polarization of the ψ(nS) and Υ(nS) states can be measured through the study of the angular distribution of the leptons produced in the dimuon decay of the quarkonium. The most general observable distribution of a parity-conserving dilepton decay of vector particles can be written as

$$W(\cos\vartheta, \varphi|\vec{\lambda}) = \frac{3/(4\pi)}{(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi), \qquad (3.1)$$

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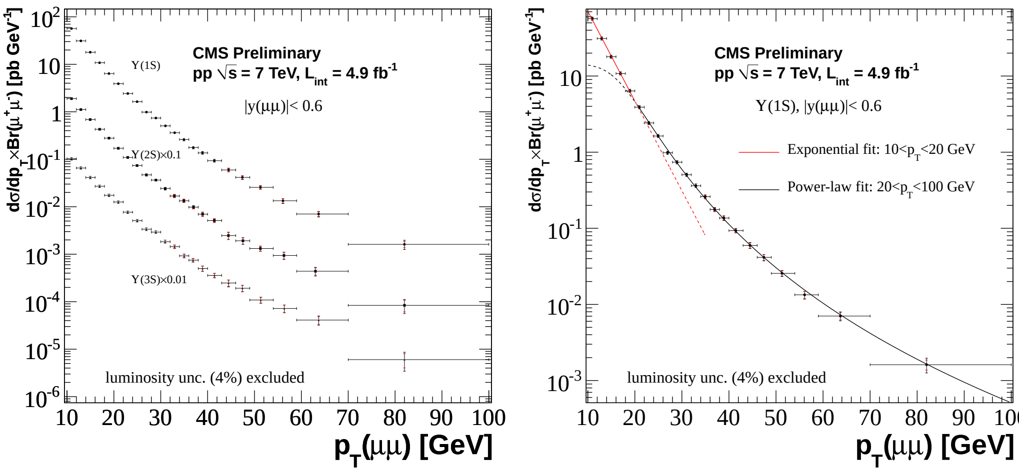

Figure 1: Left: Differential cross sections times dimuon branching ratio for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states. The $\Upsilon(2S)$ and $\Upsilon(3S)$ states are scaled by 0.1 and 0.01, respectively, for visibility purposes. Right: Fit of the $\Upsilon(1S)$ differential cross section with an exponential function for 10 $< p_{\mathrm{T}} <$ 20 GeV and a power-law function for $p_{\mathrm{T}} >$ 20 GeV.

where $\vec{\lambda} = (\lambda_\vartheta,\ \lambda_\varphi,\ \lambda_{\vartheta\varphi})$ represents the frame-dependent polarization parameters and ϑ and φ are the polar and azimuthal angles of the positive muon, μ^+, with respect to the z-axis of the chosen reference frame [7]. There are three reference frames that are important in this context: the center-of-mass helicity (HX) frame with the z-axis coinciding with the direction of the quarkonium momentum; the Collins-Soper (CS) frame [8] with the z-axis in the direction of the relative velocity of the colliding beams in the quarkonium rest frame; and the perpendicular helicity (PX) frame [9] with the z-axis orthogonal to the CS axis.

Previous work established that all angular distribution parameters have to be considered, ideally in more than one reference frame, to get a complete and robust measurement of the quarkonium polarization [10, 11, 12]. Additionally, it is beneficial to examine frame-invariant parameters, to gain further physics insight and to probe systematic effects. The CMS polarization measurements determined the frame-dependent λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$ parameters, as well as the frame-invariant quantity $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1-\lambda_{\vartheta\varphi})$, in the CS, HX and PX frames.

The analyses use an unbinned likelihood approach to determine the polarization parameters. First, events distributed as in the background model are removed from the data sample until a previously determined background fraction is reached. In the case of the ψ(nS) states, the background consists not only of mass continuum events but also of nonprompt charmonia coming from B decays. Second, the Posterior Probability Distribution (PPD) is defined from the remaining signal-like events. The numerical results and graphical representations are determined from projections of the PPD.

3.1 Υ(nS) Polarization Results

The Υ(nS) polarization is determined independently in five p_{T} bins, covering a range of 10 to 50 GeV, and in two slices of rapidity (0. – 0.6, 0.6 – 1.2). Results showing the frame-dependent and frame-invariant parameters in the CS, HX and PX frames, as well as details concerning the analysis, can be found in Ref. [5, 13]. No strong polarization has been observed for the Υ(nS) mesons.

Figure 2 shows the λ_ϑ parameter in comparison to a NLO NRQCD fit, where the colour octet matrix elements are left as free parameters [14]. The theoretical calculations of the Υ(1S) and Υ(2S) include free parameters reflecting the feed-down contributions from χ_b states while the Υ(3S) is assumed to be exclusively directly produced, thereby having much less freedom in the fit.

3.2 Prompt ψ(nS) Polarization Results

The polarization of the J/ψ meson is measured for $14 < p_\mathrm{T} < 70$ GeV in two $|y|$ bins (0. – 0.6, 0.6 – 1.2) while the ψ(2S) polarization covers a p_T range of 14 to 50 GeV and includes an additional $|y|$ bin from 1.2 to 1.5.

Figure 3 displays the $\tilde{\lambda}$ parameter in the CS, HX and PX frames for $|y| < 0.6$. The good agreement of the results in all three reference frames indicates the absence of unaccounted systematic uncertainties. The same consistency has been observed for the other rapidity bins.

Figure 4 shows the results of the three frame-dependent polarization parameters, λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$, for the J/$\psi$ and ψ(2S) mesons as a function of dimuon p_T in different rapidity ranges. As for the Υ(nS) states, no significant ψ(nS) polarizations have been observed. As shown in Fig. 5, the experimental results disagree with NLO NRQCD predictions based on a fit of color octet matrix elements to cross-section measurements [15]. The theory predicts the polarization only for directly produced J/ψ's while the measurement also includes feed-down contributions from higher states, which makes the comparison difficult. Instead, the experimental and theoretical results for the ψ(2S) are directly comparable since the ψ(2S) does not suffer from feed-down contributions with unknown polarizations. Additional information and results can be found in Ref. [16, 17].

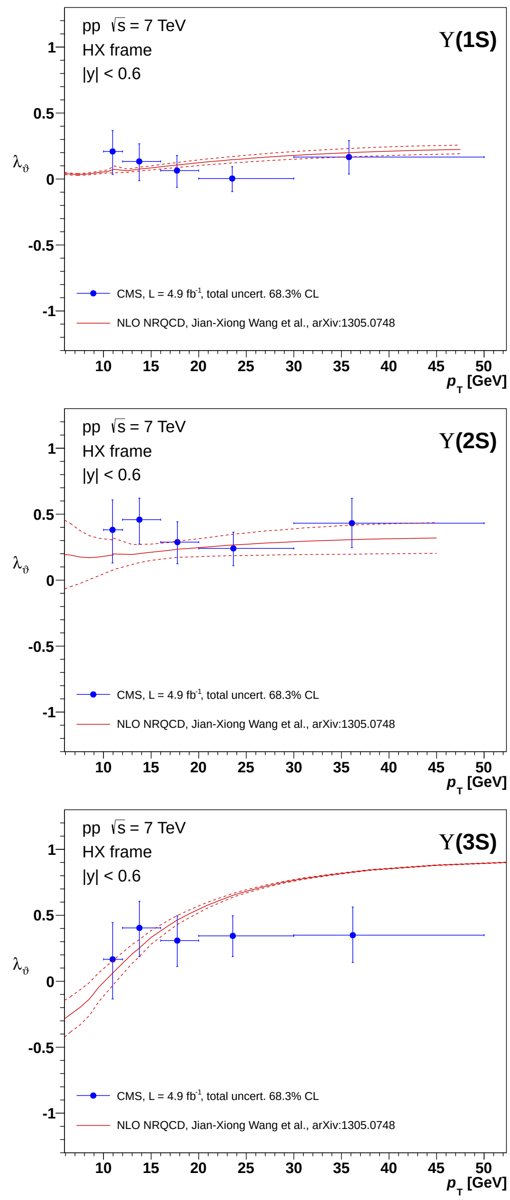

Figure 2: λ_ϑ parameter of the Υ(1S) (top), Υ(2S) (middle) and Υ(3S) (bottom) states measured in the HX frame as a function of the dimuon p_T for $|y| < 0.6$ compared to NLO NRQCD predictions [14]. The theoretical calculations of the Υ(1S) and the Υ(2S) include feed-down contributions.

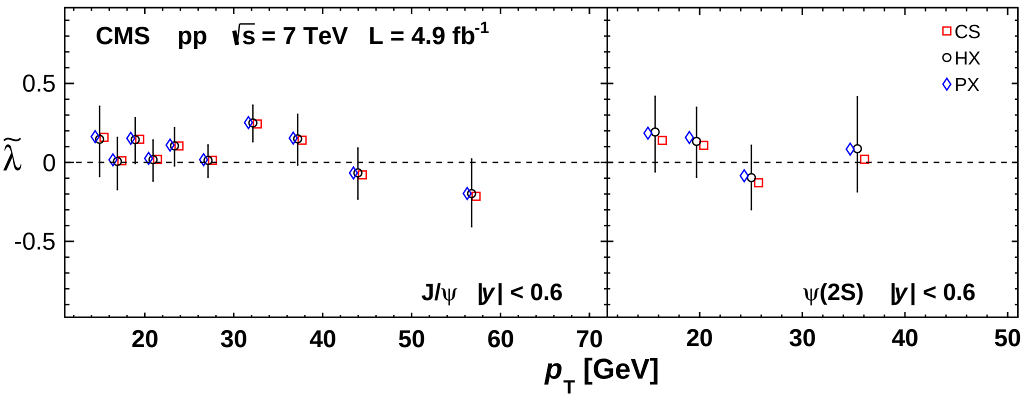

Figure 3: Measurement of the frame-invariant $\tilde{\lambda}$ parameter for the J/ψ (left) and ψ(2S) (right) as a function of dimuon p_{T} for $|y| < 0.6$. The error bars represent total uncertainties at the 68.3% confidence level (CL) in the HX frame.

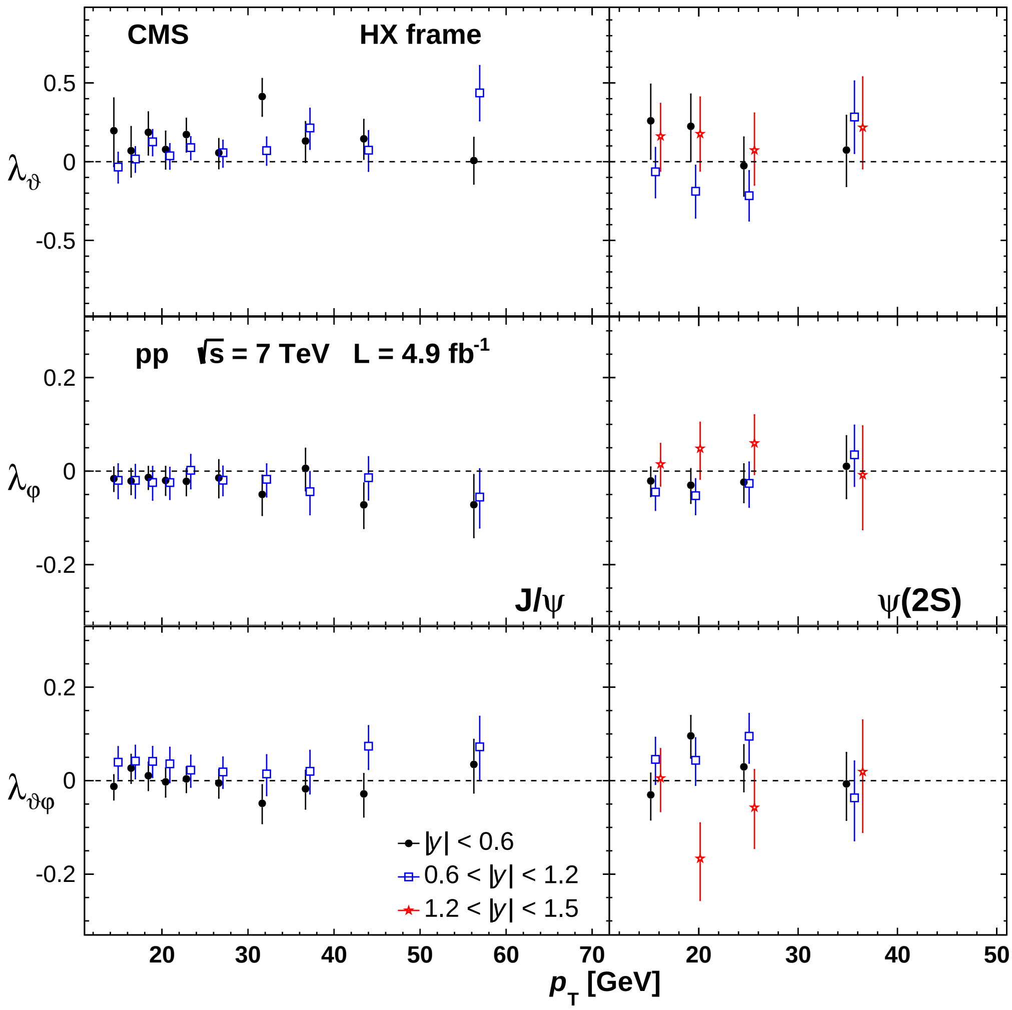

Figure 4: Measurement of the λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$ parameters (top to bottom) for the prompt J/ψ (left) and prompt ψ(2S) (right) in the HX frame as a function of dimuon p_{T} for all rapidity ranges. The error bars represent total uncertainties at the 68.3% confidence level (CL).

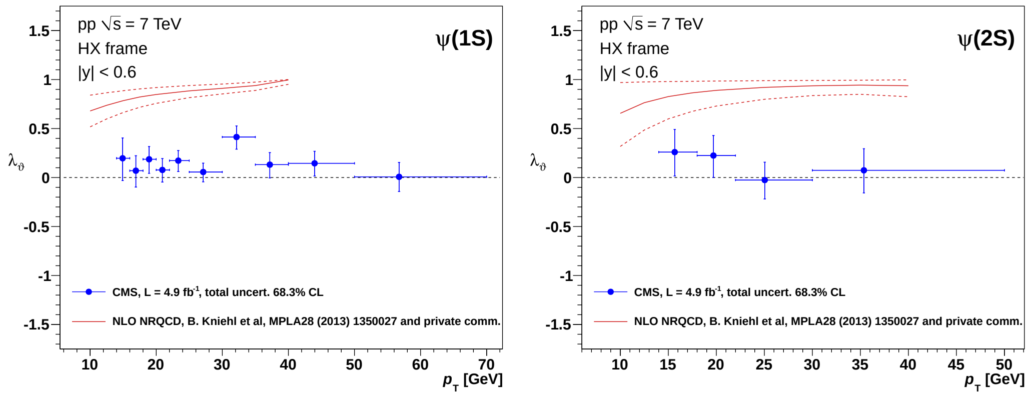

Figure 5: λ_ϑ parameter of the prompt J/ψ (left) and prompt ψ(2S) (right) measured in the HX frame as a function of the dimuon p_T, for $|y| < 0.6$, compared to predictions for the directly produced ψ(nS) calculated in NLO NRQCD [15].

4. Summary

CMS determined the p_T differential cross sections of the Υ(1S), Υ(2S) and Υ(3S) mesons using the previously published polarization results. The measurement covers a kinematic range of $10 < p_T < 100$ GeV and $|y| < 0.6$. A change in the shape of the differential cross sections has been observed, suggesting a change in the nature of the production process.

Polarization measurements for the Υ(nS) and the prompt ψ(nS) states were conducted by CMS. The frame-dependent polarization parameters, λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$, as well as the frame-invariant quantity $\tilde{\lambda}$ have been determined in the CS, HX and PX frames. The measurements extend beyond the p_T and $|y|$ ranges probed by previous experiments and show no evidence of large polarizations in the explored kinematic regions. The experimental results are in disagreement with current NLO NRQCD calculations.

All measurements are based on a dimuon sample collected in proton-proton collisions at $\sqrt{s} =$ 7 TeV, in 2011, corresponding to a total integrated luminosity of 4.9 fb^{-1}.

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