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Υ(nS) Polarization Results: Summary from CMS and CDF

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Studies of heavy quarkonium production and polarization play an important role in the understanding of quantum chromodynamics. The CMS and CDF Υ(nS) polarization analyses are the most comprehensive measurements of quarkonium polarization made so far. The three frame-dependent polarization parameters, λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$, plus the frame-invariant parameter $\tilde{\lambda}$ are measured in different reference frames as a function of transverse momentum. The results of the two experiments are in good agreement. The polarization parameters are measured to be small in the reference frames under study, excluding large transverse or longitudinal polarizations, especially for the Υ(3S) state, which is less affected by feed-down contributions with unknown polarization. These observations are in disagreement with the available theoretical expectations for high-energy hadron collisions.

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1. Introduction

Studies of heavy quarkonium states are very important to probe quantum chromodynamics (QCD) and improve our understanding of it, given that the heavy quark masses allow non-perturbative calculations. J/ψ and Υ cross sections can be described by nonrelativistic QCD calculations (NRQCD), dominated by color octet production [1]. NRQCD predicts a large transverse polarization, while the next-to-leading order (NLO) color singlet model (CSM) [2] indicates large longitudinal polarization. Therefore, the quarkonium polarization is a powerful observable to discriminate between the theoretical models [3].

The polarization of the Υ states can be measured through the study of the angular distribution of the leptons produced in the $\Upsilon \to \mu^+\mu^-$ decay channel. The most general observable distribution of a parity-conserving decay of vector particles can be written as

$$W(\cos\vartheta, \varphi|\vec{\lambda}) \propto \frac{1}{(3+\lambda_\vartheta)}(1+\lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi), \tag{1.1}$$

where $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ represent 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 [4]. There are three reference frames that are important in this context: the center-of-mass helicity (HX) frame, where the z-axis coincides with the direction of the Υ momentum; the Collins-Soper (CS) frame [5], where the z-axis is the direction of the relative velocity of the colliding beams in the Υ rest frame; and the perpendicular helicity (PX) frame [6], whose z-axis is orthogonal to the CS axis.

It has been established by Refs. [4, 7, 8, 9] that it is important to consider the full angular distribution in various reference frames. Furthermore, it is beneficial to additionally examine frame invariant parameters to probe systematic effects and to get supplementary physical information.

The CMS and CDF experiments were the first to determine all three frame-dependent polarization parameters, λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$, in various reference frames using the $\Upsilon \to \mu^+\mu^-$ decay channel. Moreover, the measurements were completed with the frame-invariant parameter, $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1-\lambda_{\vartheta\varphi})$, which provides a very useful intrinsic test of the reliability of the whole analysis chain [10, 11].

2. CDF Υ(nS) polarization analysis

CDF used a dimuon sample collected in p$\bar{\text{p}}$ collisions at the center of mass energy of $\sqrt{s} = 1.96$ TeV, corresponding to a total integrated luminosity of 6.7 fb^{-1}, to analyze the polarization of the Υ(1S), Υ(2S) and Υ(3S) mesons. Approximately 550 000 Υ(1S), 150 000 Υ(2S) and 76 000 Υ(3S) candidates with a dimuon transverse momentum, $p_\text{T} < 40$ GeV, and rapidity, $|y| < 0.6$, were contained in this sample. The analysis was performed separately in eight p_T bins and two reference frames: the CS and the HX frame.

Fig. 1 shows the results of the three frame-dependent polarization parameters, λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$, for the Υ(nS) states in the HX frame as a function of Υ p_T. The corresponding results for the frame-invariant parameter, $\tilde{\lambda}$, in the HX and CS frames, are displayed in Fig. 2. The values of the different reference frames are in good agreement as required in the absence of unaccounted

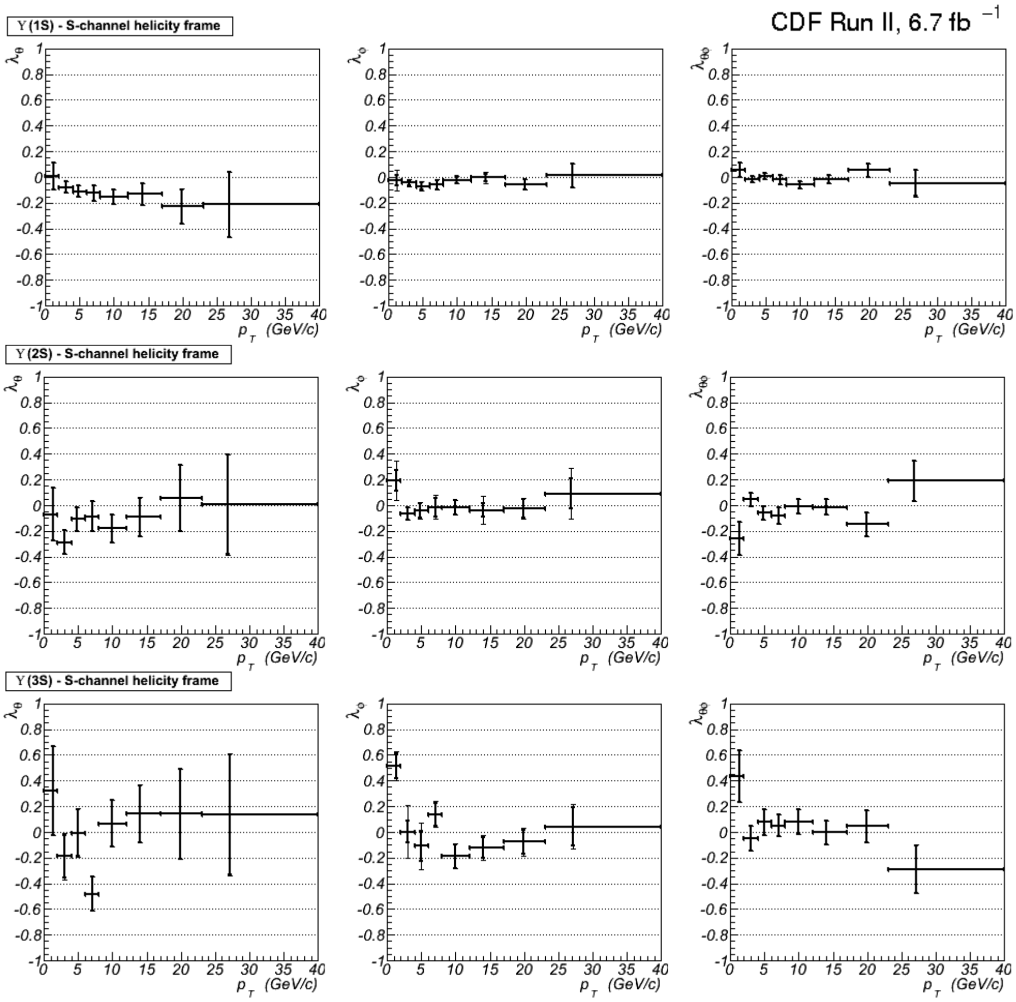

Figure 1: λ_ϑ (left), λ_φ (middle), and $\lambda_{\vartheta\varphi}$ (right) parameters for the Υ(1S) (top), Υ(2S) (middle) and Υ(3S) (bottom) in the HX frame for $|y| < 0.6$, as measured by CDF. The thick error bars represent statistical uncertainties while the thin bars show the statistical plus systematical uncertainties.

systematic uncertainties. The current CDF measurement agrees with the previous CDF measurement [12] where only the λ_ϑ parameter in the HX frame was determined. More details regarding the CDF polarization analysis can be found in Ref. [11].

3. CMS Υ(nS) polarization analysis

CMS based its Υ(nS) polarization analysis on a dimuon sample collected in pp collisions in 2011 at $\sqrt{s} = 7$ TeV. The data corresponds to a total integrated luminosity of 4.9 fb^{-1}. Approximately 252 000 Υ(1S), 94 000 Υ(2S) and 58 000 Υ(3S) candidates with a dimuon transverse momentum, $10 < p_\mathrm{T} < 50$ GeV, and rapidity, $|y| < 1.2$, were analyzed in five transverse momentum bins and two rapidity ranges in the HX, PX and CS frame.

Fig. 3 shows the results of the parameters λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$ for the Υ(1S), Υ(2S) and Υ(3S) states in the HX frame for $|y| < 0.6$. Systematic uncertainties dominate the total error at low p_T

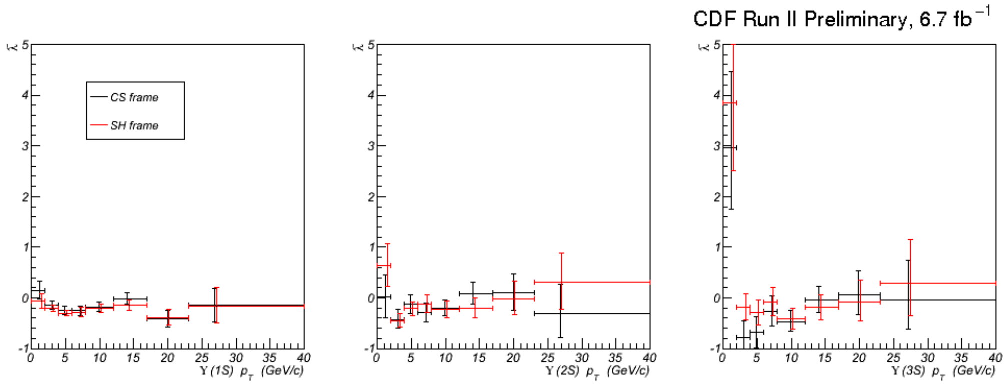

Figure 2: $\tilde{\lambda}$ parameter for the Υ(1S), Υ(2S), and Υ(3S) states (left to right) in the CS and HX (SH) frames for $|y| < 0.6$, as measured by CDF.

while the statistical uncertainties are more important at high p_T. Similar results are obtained in the rapidity range $0.6 < |y| < 1.2$ [13]. Fig. 4 displays the results of the $\tilde{\lambda}$ parameter in the HX frame as well as the values obtained in the PX and CS frames. The $\tilde{\lambda}$ values in the different reference frames are in good agreement indicating that there are no unaccounted systematic effects. More details regarding the CMS analysis can be found in Ref. [10].

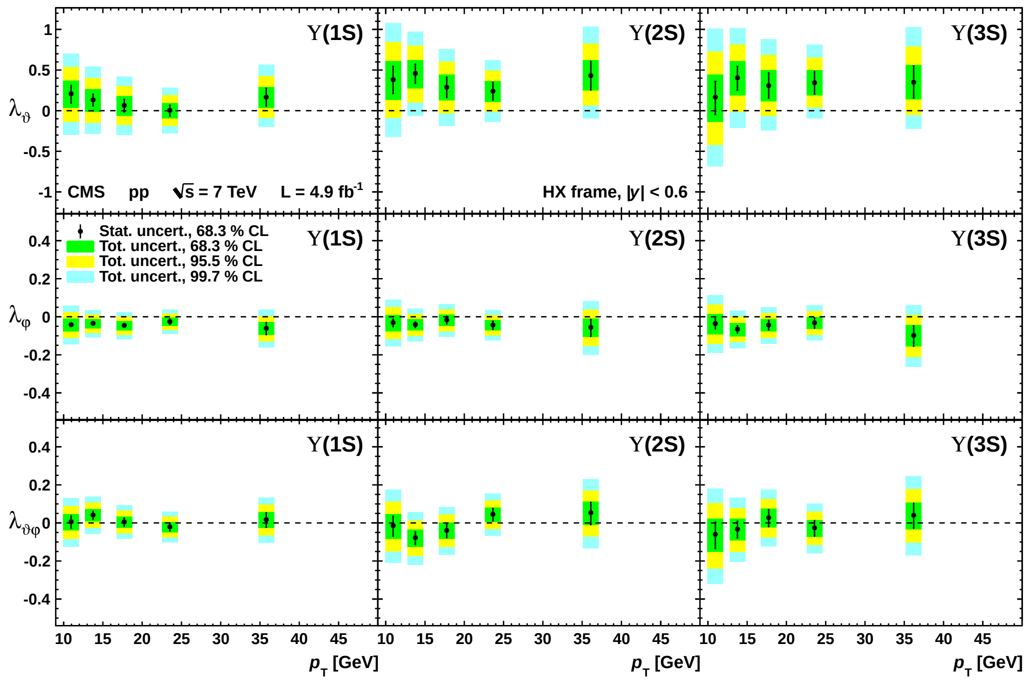

Figure 3: λ_ϑ (top), λ_φ (middle), and $\lambda_{\vartheta\varphi}$ (bottom) parameters for the Υ(1S) (left), Υ(2S) (middle), and Υ(3S) (right) in the HX frame for $|y| < 0.6$, as measured by CMS. The error bars indicate the 68.3% confidence level (CL) interval neglecting systematic uncertainties. The error bands represent the 68.3%, 95.5%, and 99.7% CL intervals of the total uncertainties.

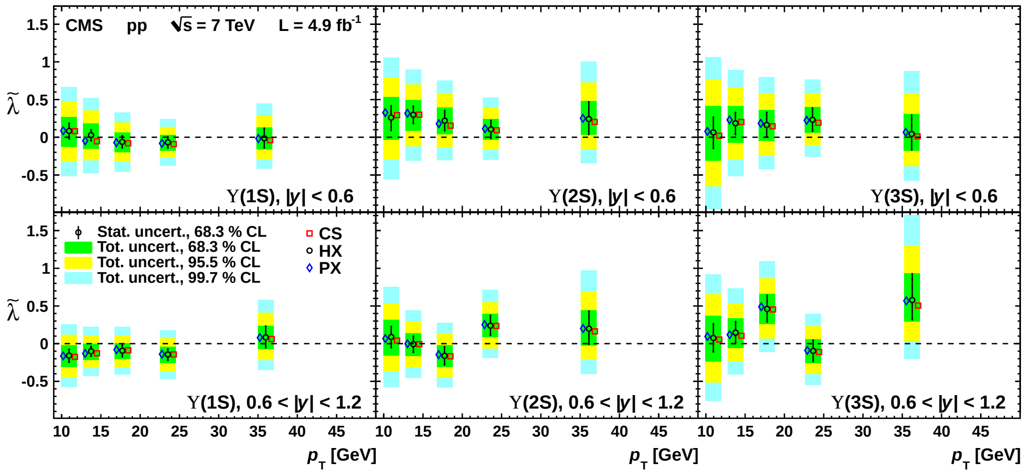

Figure 4: $\tilde{\lambda}$ parameter for the Υ(1S), Υ(2S), and Υ(3S) states (left to right) in the HX, CS, and PX frames for $|y| < 0.6$ (top) and $0.6 < |y| < 1.2$ (bottom), as measured by CMS.

4. Discussion of mutual agreement between the CMS and CDF measurements

Fig. 5 shows the comparison of the outcome of the Υ(nS) polarization analysis conducted by the CMS and CDF experiment. The λ_ϑ parameter of the Υ(1S) in the CS frame is displayed on the left side while the right side exhibits the same parameter for the Υ(3S) state in the HX frame. In general, the results of the two experiments are in good agreement, both showing only small values for the different polarization parameters. Therefore, strong longitudinal or transverse polarizations of the Υ(nS) mesons are excluded. Moreover, the values of the polarization parameters are small in all frames under study, indicating that there is no remaining undetected significant polarization due to smearing effects induced by unfortunate frame choices.

Both CMS and CDF determined the polarization of inclusively produced Υs without making a distinction between Υ mesons that are directly produced and those coming from higher χ_b states. The feed-down contribution with unknown polarization is smallest in case of the Υ(3S) state, thus making it the most interesting state. Since theoretical predictions calculate the polarization of directly produced Υs, a comparison to theory is most reliable for the Υ(3S) meson. Fig. 5 (right) shows a comparison of the experimental results to theoretical NLO-NRQCD [1] and NNLO*-CSM [2] calculations. The predictions are in disagreement with the experimental data.

5. Summary

The polarizations of the Υ(nS) mesons decaying to two muons have been determined as a function of the transverse momentum by the CMS and the CDF experiment in different reference frames, using both frame-dependent and frame-independent parameters. The results exclude large transverse or longitudinal Υ(nS) polarizations and seem to be in disagreement with theoretical predictions.

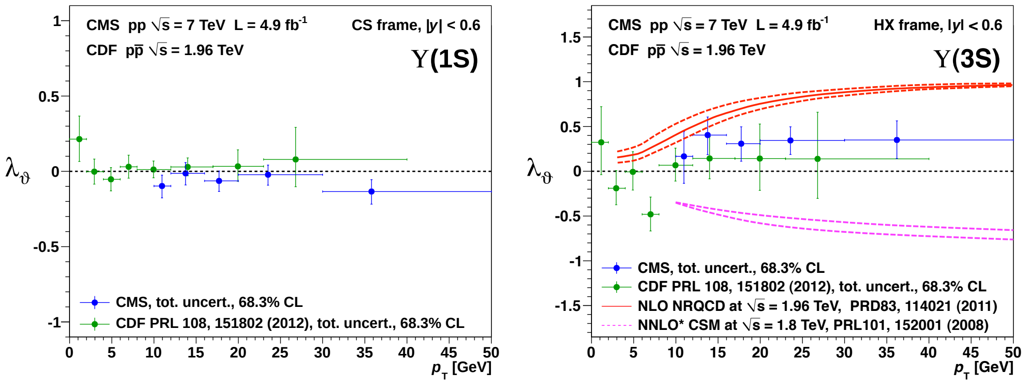

Figure 5: Left: λ_ϑ for the $\Upsilon(1S)$ in the CS frame and in the range $|y| < 0.6$, as measured by CMS and CDF. Right: λ_ϑ for the $\Upsilon(3S)$ in the HX frame and in the range $|y| < 0.6$, as measured by CMS, compared to the CDF results and to NLO-NRQCD and NNLO*-CSM calculations.

References

[1] B. Gong, J.-X.Wang, H.-F. Zhang. QCD corrections to Υ production via color-octet states at the Tevatron and LHC. *Phys. Rev. D*, 83:114021, 2011

[2] P. Artoisenet, J. Campbell, J. P. Lansberg, F. Maltoni, F. Tramontano. Υ Production at Fermilab Tevatron and LHC Energies. *Phys. Rev. Lett.*, 101:152001, 2008

[3] N.Brambilla, et al. Heavy quarkonium: progress, puzzles, and opportunities. *Eur. Phys. J. C*, 71:1534, 2011.

[4] P. Faccioli, C. Lourenço, J. Seixas, H.K. Wöhri. Towards the experimental clarification of quarkonium polarization. *Eur. Phys. J. C*, 69:657, 2010.

[5] J.C.Collins, D.E.Soper. Angular Distribution of Dileptons in High-Energy Hadron Collisions. *Phys. Rev. D*, 16:2219, 1977.

[6] E. Braaten, D. Kang, J. Lee, C. Yu. Optimal spin quantization axes for the polarization of dileptons with large transverse momentum. *Phys. Rev. D*, 79:014025, 2009.

[7] P. Faccioli, C. Lourenço, J. Seixas, H.K. Wöhri. J/ψ polarization from fixed-target to collider energies. *Phys. Rev. Lett.*, 102:151802, 2009.

[8] P.Faccioli, C.Lourenço, J.Seixas. Rotation-invariant relations in vector meson decays into fermion pairs. *Phys. Rev. Lett.*, 105:061601, 2010.

[9] P. Faccioli, C. Lourenço, J. Seixas. New approach to quarkonium polarization studies. *Phys. Rev. D*, 81:111502, 2010.

[10] CMS Collaboration. Measurement of the Υ(1S), Υ(2S) and Υ(3S) polarizations in pp collisions at $\sqrt{s} = 7$ TeV. *Phys. Rev. Lett.*, 110:081802, 2013.

[11] CDF Collaboration. Measurements of the Angular Distributions of Muons from Υ Decays in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV. *Phys. Rev. Lett.*, 108:151802, 2012.

[12] CDF Collaboration. Υ Production and Polarization in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV. *Phys. Rev. Lett.*, 88:161802, 2002

[13] See Supplemental Material at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11023.