PROCEEDINGS OF SCIENCE

Measurement of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarizations in proton-proton collisions at $\sqrt{s} = 7$ TeV with the CMS experiment

Valentin Knünz[*†]
Institute of High Energy Physics
on behalf of the CMS collaboration
E-mail: valentin.karl.knunz@cern.ch

The polarizations of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons produced in proton-proton collisions at $\sqrt{s}$ = 7 TeV are measured using a data sample collected with the CMS detector at the LHC, corresponding to an integrated luminosity of approximately 5 fb^{-1}. The measurements are based on the analysis of the dimuon decay angular distributions, analyzed in three different polarization frames, and are presented as a function of the Υ transverse momentum, in two rapidity ranges. The measurement of the polarization parameters, λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$ is complemented by the determination of the frame-invariant quantity $\tilde{\lambda}$, which provides an intrinsic test of the whole analysis chain and of the extracted physical information. The results are in disagreement with the available theoretical predictions for high-energy hadron collisions.

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*Speaker.
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1. Introduction

Detailed experimental studies of quarkonium production can deliver key information for the understanding of quantum chromodynamics (QCD). Various theoretical models are able to provide predictions for quarkonium production observables, including differential cross sections and polarization properties of the decaying quarkonium states. Due to their high mass, quarkonia can be treated as approximately non-relativistic systems. This approximation is used by certain models, simplifying the treatment of non-perturbative effects [1].

While the measured differential cross sections of J/ψ and Υ states at the Tevatron and the LHC can be well reproduced by non-relativistic QCD (NRQCD), its prediction of transverse polarization for these states [2] tends to be in disagreement with the CDF measurements [3, 4]. Furthermore, the experimental results of Υ polarization of D0 [5] and CDF [4] are contradictory. Due to its high mass, the Υ states should fulfill the non-relativistic approximation better than the J/ψ, especially at high values of transverse momentum p_{T}, making the Υ polarization an interesting test of NRQCD.

The polarization of a quarkonium state can be measured through the analysis of the angular distribution of the two muons produced in the decay $\Upsilon \to \mu^+\mu^-$. The most general angular decay distribution for a $J^{\mathrm{PC}} = 1^{--}$ state is [6]

$$W(\cos\vartheta,\varphi|\vec{\lambda}) \propto \frac{1}{(3+\lambda_\vartheta)}(1+\lambda_\vartheta\cos^2\vartheta+\lambda_\varphi\sin^2\vartheta\cos2\varphi+\lambda_{\vartheta\varphi}\sin2\vartheta\cos\varphi)\,, \tag{1.1}$$

with ϑ and φ the polar and azimuthal angles, respectively, of the positive muon with respect to the quantization axis z of the chosen polarization frame. As discussed in Refs. [6, 7, 8, 9, 10], measurements of quarkonium polarization should consider the full angular decay distribution and all the angular distribution parameters $\vec{\lambda} = (\lambda_\vartheta,\lambda_\varphi,\lambda_{\vartheta\varphi})$ in various polarization frames, as well as the frame-invariant polarization parameter $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1-\lambda_\varphi)$.

2. Υ(nS) Polarization Analysis

This document presents the measurement of the Υ(1S), Υ(2S) and Υ(3S) polarizations in pp collisions at $\sqrt{s}$ = 7 TeV, collected with the CMS detector in 2011 [11]. The dataset corresponds to an integrated luminosity of 4.9 fb^{-1} and contains approximately 252 000 Υ(1S), 94 000 Υ(2S) and 58 000 Υ(3S) mesons, after the application of all selection criteria.

The events were collected using a two-level trigger system. The hardware-based first level uses information from the muon systems to select events with two muons. The second level, consisting of a processor farm, requires opposite-sign muon pairs with an invariant mass $8.5 < M < 11.5$ GeV, rapidity $|y| < 1.25$ and $p_{\mathrm{T}} > 5$ or 7 GeV.

Polarization parameters are measured in three reference frames, characterized by different quantization axes in the production plane defined by the colliding proton momenta as seen in the Υ rest frame. The helicity axis (HX) is defined to be aligned along the momentum direction of the decaying quarkonium, the Collins-Soper axis (CS) is defined as the average of the two beam directions, and the perpendicular-helicity axis (PX) is defined to be orthogonal to the CS axis.

The dimuons used in the analysis are formed by combining two opposite-sign muons satisfying several quality criteria. Defining the pseudo-rapidity $\eta = -\ln\tan(\vartheta/2)$, with ϑ the polar angle measured with respect to the beam axis, the muons are restricted to a fiducial region $|\eta| < 1.6$. Furthermore, their p_T must be 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. The analysis is presented as function of dimuon p_T covering the kinematic range of $10 < p_\mathrm{T} < 50$ GeV, in two ranges of dimuon rapidity, $|y| < 0.6$ and $0.6 < |y| < 1.2$.

The single-muon trigger, reconstruction and identification efficiencies are measured as function of muon p_T and $|\eta|$ with the data-driven *tag & probe* method. Dimuon efficiencies are assumed to factorize, as function of the muon kinematics, as the product of the two single-muon efficiencies. This technique has been validated with detailed Monte Carlo (MC) simulation studies.

The dimuon mass spectrum in the Υ mass region is modeled by Crystal-Ball functions representing the signal peaks and a second degree polynomial to model the continuum background. A dimuon mass window of 1σ around each Υ(nS) pole mass is defined to ensure that the overlap between these mass windows is negligible. The fraction of background events in the chosen signal region, f_{BG}, is 4–8%, 9–18%, and 12–28%, for the Υ(1S), Υ(2S), and Υ(3S), respectively.

The average event kinematics of the continuum background events is modeled by a weighted sum of the distributions of the events in the mass sidebands, with the assumption that the background kinematics changes monotonically as function of dimuon mass. Variations of the relative weights are propagated to the systematic uncertainties. Background events in the data sample are subtracted on an event-by-event basis using a likelihood ratio approach: depending on the event kinematics $(p_\mathrm{T}, |y|, M, \cos\vartheta, \varphi)$ and the likelihood for the event to be a background event, a fraction f_{BG} of events is subtracted from the sample.

The remaining *signal-like* events (i) are used to calculate the posterior probability distribution (PPD) $\mathscr{P}(\vec{\lambda})$ as function of the polarization parameters $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$,

$$\mathscr{P}(\vec{\lambda}) = \prod_i \mathscr{E}(\vec{p}_1^{\,(i)}, \vec{p}_2^{\,(i)}) , \tag{2.1}$$

where $\mathscr{E}$ denotes the event probability distribution as function of the muon kinematics. With this approach, it is possible to assign to each event an efficiency determined from the full event kinematics of the muons.

Due to the random nature of the background subtraction, the procedure is repeated 50 times to reduce the associated statistical fluctuations. The PPD is then obtained as the average of the PPDs calculated over the 50 different ensembles of signal-like events.

The analysis framework has been tested with pseudo-experiments based on simulated samples, for various assumptions of signal and background polarizations. These pseudo-experiments are used to evaluate the systematic uncertainties associated to the determination of the efficiencies and of the framework itself.

3. Results

The final PPD is an envelope of all PPDs corresponding to the ranges of hypotheses covered by each source of systematic uncertainty. Figure 1 shows two-dimensional projections of the final PPD for the Υ(1S) at $|y| < 0.6$ and $30 < p_\mathrm{T} < 50$ GeV. The highest posterior probability of the one-dimensional projection is used to evaluate the best value for each polarization parameter. The corresponding uncertainties are expressed in confidence levels (CL), defined as the interval $[\lambda_1, \lambda_2]$,

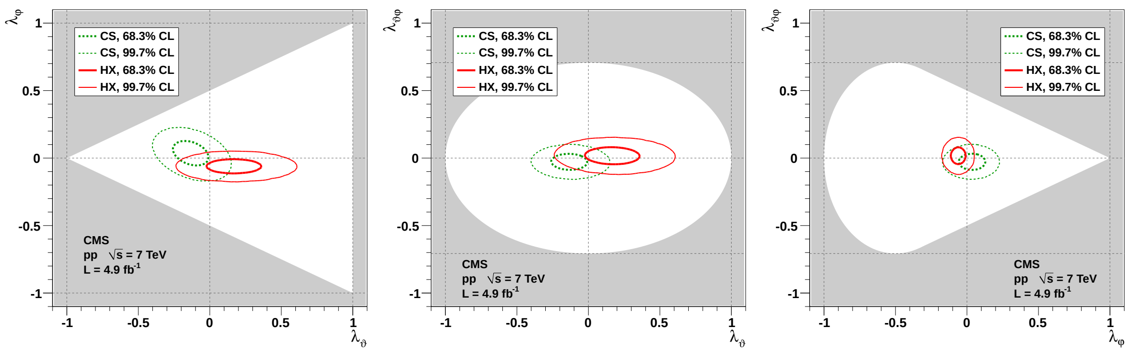

Figure 1: λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$ 2D projections of the PPD for $\Upsilon(1S)$ with $30 < p_T < 50$ GeV and $|y| < 0.6$. The shaded areas represent physically forbidden parameter space regions [10].

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.

Figures 2 and 3 show the 68.3%, 95.5%, and 99.7% CL intervals of the one-dimensional projections of the PPD for the frame-dependent polarization parameters λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$ in the HX frame as function of p_T, for the rapidity ranges $|y| < 0.6$ and $0.6 < |y| < 1.2$, respectively. Figure 4 shows the corresponding results of the frame-invariant parameter $\tilde{\lambda}$, for $|y| < 0.6$ and $0.6 < |y| < 1.2$ in the HX frame, together with the central values obtained in the CS and PX frames. The results of the three frames are in good agreement, indicating the absence of unaccounted systematic effects.

Figure 5 compares the results of this analysis to recent CDF Υ(nS) polarization measurements [4] (left) and to NLO-NRQCD [2] and NNLO*-CSM [12] calculations (right). Good agreement between the results of the present analysis and the CDF results is observed for $\Upsilon(1S)$ and

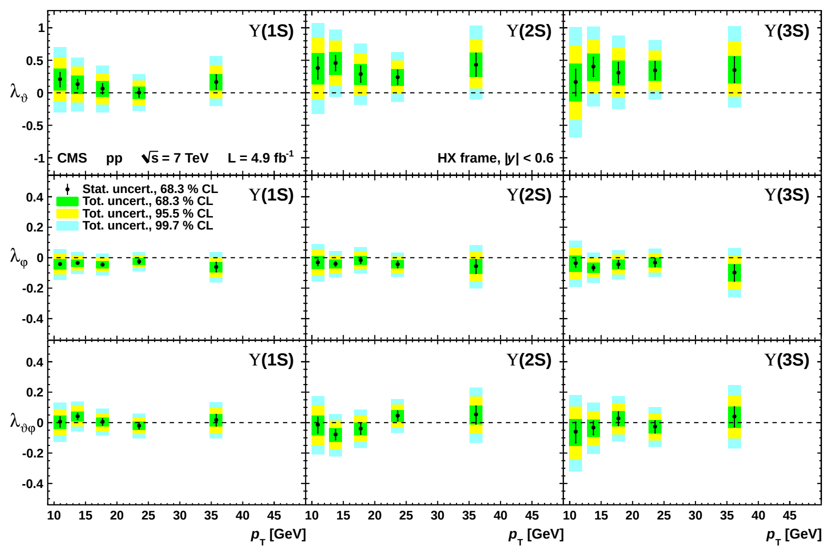

Figure 2: λ_ϑ (top), λ_φ (middle), and $\lambda_{\vartheta\varphi}$ (bottom) parameters for the $\Upsilon(1S)$ (left), $\Upsilon(2S)$ (middle), and $\Upsilon(3S)$ (right), in the HX frame, for $|y| < 0.6$ as a function of dimuon p_T. The bars indicate the 68.3% CL interval neglecting systematic uncertainties.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

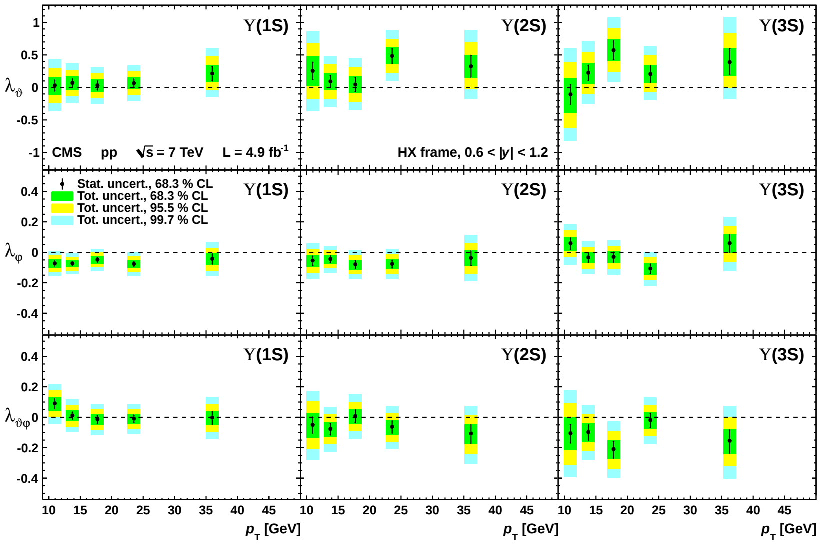

Figure 3: Same as previous Figure, for the rapidity range $0.6 < |y| < 1.2$.

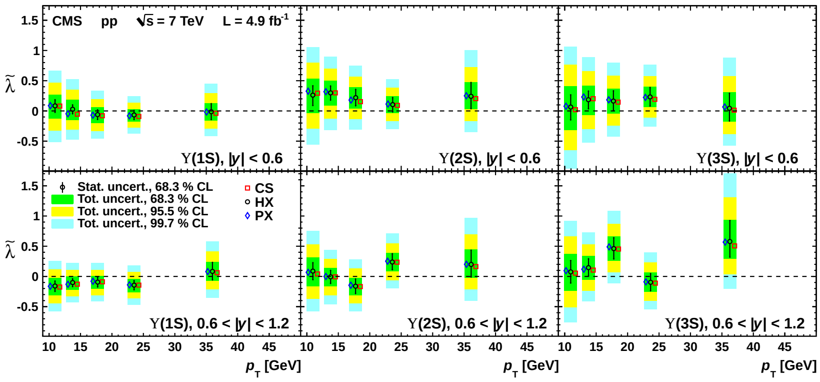

Figure 4: $\tilde{\lambda}$ for the $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(3\mathrm{S})$ states (left to right), as a function of p_{T}, in the HX, CS, and PX frames, for the $|y| < 0.6$ (top) and $0.6 < |y| < 1.2$ (bottom) ranges.

$\Upsilon(3\mathrm{S})$. While CDF reaches lower ranges of p_{T}, the CMS analysis is able to reach better precision at high p_{T}. The comparison with the model calculations shows poor agreement for any of the two models under consideration.

4. Summary

The $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ polarizations have been measured, using a dataset collected by CMS in pp collisions at $\sqrt{s} = 7$ TeV. The frame-dependent parameters λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$ and the frame-independent parameter $\tilde{\lambda}$ have been determined, as function of the Υ p_{T} in two rapidity ranges and in three different polarization frames.

The polarization parameters are small in all frames, excluding large transverse or longitudinal $\Upsilon(\mathrm{nS})$ polarizations, beyond the p_{T} and y ranges probed by previous experiments. The results tend to be in disagreement with theoretical expectations for high-energy hadron collisions.

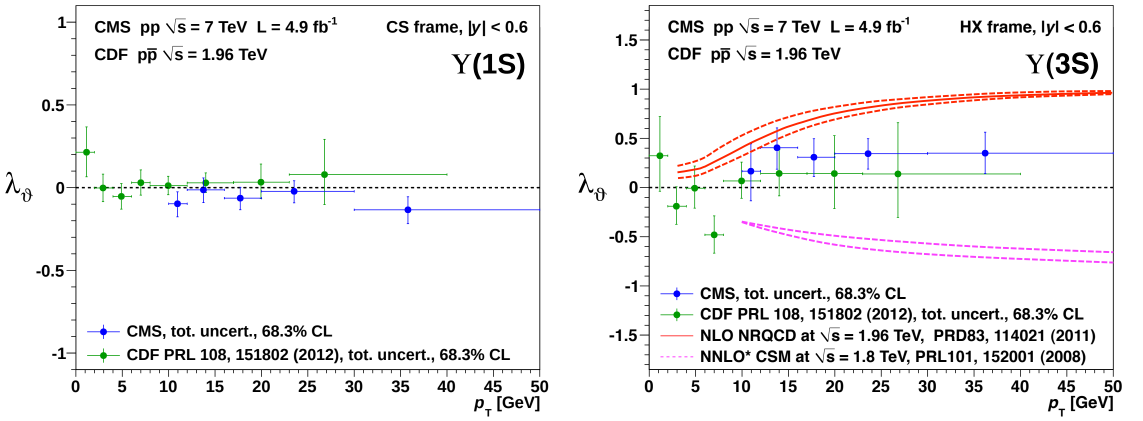

Figure 5: Left: λ_ϑ for the $\Upsilon(1S)$ in the CS frame and in the range $|y| < 0.6$, compared to the CDF results [4]. Right: λ_ϑ for the $\Upsilon(3S)$ in the HX frame and in the range $|y| < 0.6$, compared to the CDF results [4] and to NLO-NRQCD [2] and NNLO*-CSM [12] calculations.

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