\( \Upsilon(nS) \) polarizations in pp collisions at \( \sqrt{s} = 7 \) and \( 8 \) TeV by the LHCb collaboration

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Abstract. A polarization measurement carried out for the \( \Upsilon(1S) \), \( \Upsilon(2S) \) and \( \Upsilon(3S) \) mesons produced in pp collisions at \( \sqrt{s} = 7 \) and \( 8 \) TeV is presented. Data samples used for the polarization measurement were collected by the LHCb experiment during the 2011 and 2012 data taking runs with integrated luminosities of 1 and 2 fb\(^{-1} \), respectively. The measurement has been performed in three polarization frames, using an angular distribution analysis of the \( \Upsilon \rightarrow \mu^+\mu^- \) decays in the kinematic region of the \( \Upsilon \) transverse momentum \( p_{\Upsilon T} < 30 \) GeV/c and rapidity \( 2.2 < y_{\Upsilon} < 4.5 \). No large polarization is observed.

1. Introduction
It is already forty years since the discovery of the first bottomonium state, the \( \Upsilon(1S) \) meson \([1]\), but studies of heavy quarkonium production continue to play an important role in the development of quantum chromodynamics (QCD) \([2]\). According to the current theoretical framework, nonrelativistic QCD (NRQCD) \([3, 4]\), inclusive production of a heavy quarkonium is viewed as a two-step process. In the first step, a heavy quark-antiquark pair, \( Q\bar{Q} \), is perturbatively created in a color singlet or color octet state, and then, in the second step, the hadronization process non-perturbatively transforms the \( Q\bar{Q} \) pair into an observable colorless bound state. The non-perturbative transitions are described by long-distance matrix elements which are conjectured to be independent of production processes in the first step, and need to be extracted experimentally.

The most distinct signature of the first NRQCD calculations \([5, 6, 7, 8]\) was the prediction of transverse polarization for S-wave quarkonium states (such as the \( J/\psi \), \( \psi(2S) \) and \( \Upsilon(nS) \) mesons) directly produced (i.e. not coming from decays) at large transverse momentum in high-energy hadron collisions. NRQCD calculations for promptly produced heavy quarkonia (if charmonia then those not coming from b-hadron decays) are complicated by feed-down (electromagnetic or hadronic transitions) from higher level states.

Full NLO calculations \([9]\) performed for the \( \Upsilon(1S) \), \( \Upsilon(2S) \) and \( \Upsilon(3S) \) mesons (shortly denoted by \( \Upsilon \)), including effects of feed-down contributions for the \( \Upsilon(1S) \) and \( \Upsilon(2S) \) but not for the \( \Upsilon(3S) \), give very small transverse polarizations for the first two bottomonium states and a large transverse polarization for the third state. These calculations were done before LHCb obtained that the fractions of \( \Upsilon \) mesons originating from \( \chi_b \) decays are around 30–40% for high transverse momenta, \( p_{\Upsilon T} > 20 \) GeV/c \([10]\). The \( \Upsilon(3S) \) was considered as almost feed-down free state before. Although taking into account feed-down contributions improves the description of \( \Upsilon \) polarization,
there are still problems in describing the J/ψ polarization [11] (even with considering feed-down) and the ψ(2S) polarization [12] (which includes negligible feed-down contributions).

The angular distribution of muons from the \( \Upsilon \rightarrow \mu^+\mu^- \) decay can be written as [13 14 15]

\[
\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi} \frac{1}{3 + \lambda_0} \left( 1 + \lambda_0 \cos^2 \theta + \lambda_{\theta\phi} \sin 2\theta \cos \phi + \lambda_\phi \sin^2 \theta \cos 2\phi \right),
\]

where the angular quantities \( \Omega = (\cos \theta, \phi) \) describe a direction of \( \mu^+ \) in the \( \Upsilon \) rest frame with respect to some specified axes, \( \vec{\lambda} = (\lambda_0, \lambda_{\theta\phi}, \lambda_\phi) \) are the angular distribution parameters directly related to the spin-1 density-matrix elements [13 16 17]. The parameter \( \lambda_0 \) is a measure of spin-alignment, and can be expressed as \( \lambda_0 = (\sigma_T - 2\sigma_L) / (\sigma_T + 2\sigma_L) \), where \( \sigma_T \) (\( \sigma_L \)) is the transverse (longitudinal) component of the cross section. If the spin-alignment parameter \( \lambda_0 > 0 \) (\( \lambda_0 < 0 \)), the \( \Upsilon \) meson is called to be transversely (longitudinally) polarized in a specified frame, while the case \( \lambda_0 = \lambda_{\theta\phi} = \lambda_\phi = 0 \) means that the \( \Upsilon \) meson is unpolarized. The parameters \( \vec{\lambda} \) depend on a definition of coordinate axes specified in the \( \Upsilon \) rest frame. The following three coordinate systems are widely used in polarization analyses: helicity (HX) [18], Collins-Soper (CS) [19] and Gottfried-Jackson (GJ) [19]. The frames are specified by different directions of the spin-quantization axis, \( z \) axis, defined in the production plane of \( \Upsilon \) meson [19]. In all these frames, the \( y \) axis is normal to the production plane [15 21], and the remaining \( x \) axis completes a right-handed coordinate system.

Until recently, quarkonium polarization measurements have been reduced only to studies of the parameter \( \lambda_0 \), some times in different polarization frames. As pointed out in [15], measuring all the three polarization parameters is important from the theoretical and experimental points of view. Since from having the \( \vec{\lambda} \) in one frame, it is possible to transform them into another [15 22], and perform some cross checks of results. In particular, an important cross check is provided by a polarization parameter \( \vec{\lambda} = (\lambda_0 + 3\lambda_{\theta\phi}) / (1 - \lambda_0) \) [23 24], which is invariant for all rotations around the \( y \) axis, that is invariant in the HX, CS and GJ frames. The physical meaning of the parameter \( \vec{\lambda} \) was first recognized in [25] (see also [26 27]).

The first full angular distribution analysis of muons from the \( \Upsilon \rightarrow \mu^+\mu^- \) decays was performed by the CDF collaboration [28] using data of pp collisions at \( \sqrt{s} = 1.96 \) TeV. CDF found that the angular distributions of muons from all the three \( \Upsilon \) states are nearly isotropic in the central rapidity region \( |y^{\Upsilon}| < 0.6 \) and \( p_T^{\mu} < 40 \) GeV/c. This result is consistent with the previous CDF measurement [29], and inconsistent with the measurement performed by the D0 collaboration [30]. D0 observed the significant \( p_T^{\mu} \) dependent longitudinal polarization for the \( \Upsilon(1S) \) mesons produced in pp collisions at \( \sqrt{s} = 1.96 \) TeV, for \( |y^{\Upsilon}| < 1.8 \) and \( p_T^{\mu} < 20 \) GeV/c. The next full angular distribution analysis for the \( \Upsilon \rightarrow \mu^+\mu^- \) was performed by the CMS collaboration [31] using pp collisions data at \( \sqrt{s} = 7 \) TeV, for the rapidity ranges \( |y^{\Upsilon}| < 0.6 \) and \( 0.6 < |y^{\Upsilon}| < 1.2 \), and for \( 10 < p_T^{\mu} < 50 \) GeV/c [31]. CMS found no evidence of large transverse or longitudinal polarization for any of the three \( \Upsilon \) mesons in the explored kinematic region. The experimental situation is complicated by the result of the fixed-target experiment E866 [32], which performed the polarization measurement of the \( \Upsilon \) mesons produced in p-Cu collisions at \( \sqrt{s} = 38.8 \) GeV in \( 0 < x_F < 0.6 \) and \( p_T^{\mu} < 4 \) GeV/c. The E866 collaboration found that the \( \Upsilon(1S) \) meson is produced weakly polarized, while the \( \Upsilon(2S) \) and \( \Upsilon(3S) \) mesons are produced with a maximal transverse polarization. Although different production energies may determine different dominant contributions in the production processes, all these results underscore the need for further experimental study of the \( \Upsilon \) polarization.

The LHCb collaboration performed the full angular distribution analysis [24] for the \( \Upsilon \) mesons produced in pp collisions at \( \sqrt{s} = 7 \) and 8 TeV in the LHCb setup during the 2011 and 2012 data taking runs with integrated luminosities of 1 and 2 fb\(^{-1}\), respectively. The polarization measurement was done in the HX, CS and GJ frames in the \( \Upsilon \) kinematic range defined by \( p_T^{\mu} < 30 \) GeV/c and \( 2.2 < y^{\Upsilon} < 4.5 \).
2. LHCb detector and selection of $\Upsilon \to \mu^+\mu^-$ decays

The LHCb detector is a single-arm forward spectrometer primarily designed to look for indirect evidence of new physics in CP violation and rare decays of charm and beauty hadrons. The detector covers a unique pseudorapidity range $2 < \eta < 5$ corresponding to $\sim 4\%$ of the solid angle, but $\sim 25\%$ of all produced $b\bar{b}$ pairs fall into this geometrical acceptance. A detailed description of the LHCb detector and its performance are given in [33, 34].

The selection of $\Upsilon$ candidates is similar to those used in the previous LHCb analyses [33, 36, 37, 38]. The $\Upsilon$ candidates are formed from pairs of oppositely charged tracks reconstructed in the tracking system. Each track is required to have a good reconstruction quality and to be identified as a muon [40]. Each muon is then required to have momentum satisfying $1 < p_T < 25 \text{ GeV}/c$, $10 < p < 400 \text{ GeV}/c$ and pseudorapidity within the region $2.2 < \eta < 4.5$. The two muons are required to originate from a common vertex with a good $\chi^2$ probability of the vertex fit. In addition, the consistency of the dimuon vertex with a primary vertex is ensured via the quality requirement of a global fit, performed for each dimuon candidate using the primary vertex position as a constraint [41]. This global fit requirement also reduces the background caused by genuine muons coming from decays of long-lived charm and beauty hadrons. A large fraction of the combinatorial background is populated at large values of $|\cos \theta_{\text{GJ}}|$, where $\theta_{\text{GJ}}$ is the polar angle of $\mu^+$ in the GJ frame. To reduce this background, a requirement $|\cos \theta_{\text{GJ}}| < 0.8$ is applied. Finally, the mass of the muon pair is required to be in the range $8.8 < m_{\mu^+\mu^-} < 11.0 \text{ GeV}/c^2$.

As an example, a dimuon mass distribution of the $\Upsilon \to \mu^+\mu^-$ candidates finally selected in $6 < p_T^\Upsilon < 8 \text{ GeV}/c$ and $2.2 < y^\Upsilon < 3.0$ for $\sqrt{s} = 7 \text{ TeV}$ data set is shown in Fig. 1. The dimuon mass distribution is parametrized by the sum of three double-sided Crystal Ball functions [42, 43] for describing the $\Upsilon$ mesons and an exponential function for the combinatorial background. The parametrization is done by an unbinned extended maximum likelihood fit. The dimuon mass fit is performed in each $(p_T^\Upsilon, y^\Upsilon)$ bin, and results of the fit are then used by the sPlot analysis [44] for obtaining so called signal sWeights: $w_i^{\Upsilon(1S)}$, $w_i^{\Upsilon(2S)}$ and $w_i^{\Upsilon(3S)}$. The sWeights are assigned to each, $i$th, dimuon candidate for extracting the appropriate $\Upsilon$ signal component. The total signal yields obtained from the dimuon mass fit in the full explored range of $p_T^\Upsilon$ and $y^\Upsilon$ are $0.8 \times 10^6$ ($1.8 \times 10^6$) $\Upsilon(1S)$ candidates, $0.2 \times 10^6$ ($0.5 \times 10^6$) $\Upsilon(2S)$ candidates and $0.1 \times 10^6$ ($0.2 \times 10^6$) $\Upsilon(3S)$ candidates in $\sqrt{s} = 7 \text{ TeV}$ ($\sqrt{s} = 8 \text{ TeV}$) data set. The average mass resolution of the $\Upsilon(1S)$ peak is 42 MeV/$c^2$.
3. Polarization analysis

The polarization measurement is performed using an unbinned maximum likelihood approach already applied in the J/ψ and ψ(2S) polarization analyses [11,12]. The polarization parameters are determined from fits to the two-dimensional $(\cos \theta, \phi)$ angular distribution of $\mu^+$ from the $\Upsilon \rightarrow \mu^+\mu^-$ decay, described by Eq. 1.

In each $(p_T^\Upsilon, y^\Upsilon)$ bin, the following logarithm of the likelihood function is constructed for each $\Upsilon$ state:

$$\log \mathcal{L}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) = s_w \sum_{i=1}^{N_{tot}} w_i^\Upsilon \times \log \left[ \frac{\mathcal{P}(\cos \theta_i, \phi_i|\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)}{\mathcal{N}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)} \right],$$

(2)

where $\mathcal{P}(\cos \theta_i, \phi_i|\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \equiv 1 + \lambda_\theta \cos^2 \theta_i + \lambda_{\theta\phi} \sin 2\theta_i \cos \phi_i + \lambda_\phi \sin^2 \theta_i \cos 2\phi_i, \mathcal{N}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$ is normalization factor determined by Monte Carlo for each $\Upsilon$ meson, $w_i^\Upsilon$ is one of the $sWeights$ for the $i^{th}$ $\Upsilon$ candidate, and $N_{tot}$ is the total number of all selected $\Upsilon$ candidates in a considered $(p_T^\Upsilon, y^\Upsilon)$ bin. The constant scale factor $s_w = \sum_{i=1}^{N_{tot}} w_i^\Upsilon / \sum_{i=1}^{N_{tot}} (w_i^\Upsilon)^2$ is introduced to take into account correctly the effect of the $sWeights$ on statistical uncertainties of the $\tilde{\lambda}$ parameters obtained after the polarization fit. The influence of the $s_w$ was validated by pseudoexperiments.

The normalization factor $\mathcal{N}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$ is defined as

$$\mathcal{N}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \equiv \int d\Omega \mathcal{P}(\cos \theta, \phi|\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \times \varepsilon(\cos \theta, \phi)$$

(3)

and is calculated using simulated events. In the simulation, where the $\Upsilon$ mesons are generated unpolarized, the two-dimensional $(\cos \theta, \phi)$ angular distribution of $\mu^+$ from decays of selected $\Upsilon$ candidates is proportional to the total efficiency $\epsilon(\cos \theta, \phi)$, so $\mathcal{N}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$ is evaluated by summing $\mathcal{P}(\cos \theta_j, \phi_j|\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$ over the selected $\Upsilon$ candidates in the simulated sample

$$\mathcal{N}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \propto \sum_j e^{\mu^+\mu^-} \kappa_T \mathcal{P}(\cos \theta_j, \phi_j|\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi),$$

(4)

where $e^{\mu^+\mu^-}$ is a muon identification efficiency measured directly from data using a large sample of low-background $J/\psi \rightarrow \mu^+\mu^-$ events (no muon identification requirement was applied when selecting the $\Upsilon$ candidates in the simulated samples); $\kappa_T$ is a correction factor for MC, obtained using data-driven techniques to account for small differences between data and simulation in a tracking efficiency of muons [39,40] and in the $p_T^\Upsilon$ and $y^\Upsilon$ spectra [46,47].

4. Results and conclusions

Different sources of systematic uncertainty have been considered when determining the polarization parameters, namely systematic uncertainty related to: a) the $\Upsilon$ signal extraction procedure; b) the muon identification efficiency; c) the track reconstruction efficiency; d) a possible small difference in the trigger efficiency between data and simulation; e) correction factors for the muon identification efficiency; f) the finite size of the simulated samples. All these sources have been studied for the polarization parameters $\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi$ and $\tilde{\lambda}$ in the HX, CS and GJ frames for each $(p_T^\Upsilon, y^\Upsilon)$ bin. It was found that the most dominant systematic uncertainty is related to the finite size of MC samples, varying between 30% and 70% of the statistical uncertainty. The total systematic uncertainty for each polarization parameter is calculated as the quadratic sum of systematic uncertainties coming from all the considered sources, assuming no correlation between them. For some high-$p_T^\Upsilon$ bins the systematic and statistical uncertainties are comparable.

All the $\Upsilon$ polarization results obtained by the LHCb collaboration for data collected at $\sqrt{s} = 7$ TeV and 8 TeV are given in [21]. Here we outline the main features of the results. The
values of the parameter $\lambda_0$ obtained for the $\Upsilon$ mesons do not show any significant transverse or longitudinal polarization in all frames over the considered kinematic region. The values of the parameters $\lambda_{\theta\phi}$ and $\lambda_\phi$ are small in all frames over all ($p_T^\Upsilon$, $y^\Upsilon$) bins. All the three polarization parameters do not manifest a distinct dependence on the $y^\Upsilon$. The values of the frame invariant parameter $\tilde{\lambda}$ measured in the HX, CS and GJ frames are consistent with each other. Moreover, all values of the $\lambda$ are close to zero in all phase-space bins. In the considered phase space domain, the $\Upsilon$ polarization results corresponding to $\sqrt{s} = 7$ and 8 TeV are in good agreement with each other.

The $\tilde{\lambda}$ parameters have been checked for positivity constraints imposed on the spin-1 density-matrix [15, 21, 48, 26, 27]. The values of the $\tilde{\lambda}$ satisfy all the six positivity constraints in all frames over all phase-space bins. In particular, Fig. 2 shows regions allowed by the positivity constraints together with the parameters $\lambda_\phi$ and $\lambda_0$ measured in all ($p_T^\Upsilon$, $y^\Upsilon$) bins, for data collected at $\sqrt{s} = 7$ and 8 TeV. Further, since the $z$ axes of the HX, CS and GJ frames coincide in the limit $p_T^\Upsilon \to 0$ [15, 22], we checked this constraint and found that all values of the $\lambda$ are very similar for low-$p_T^\Upsilon$ bins in all frames. It was also found that the parameters $\lambda_{\theta\phi}$ and $\lambda_\phi$ are very close to zero in the limit $p_T^\Upsilon \to 0$, in accordance with kinematic constraints pointed out in [14].

Figs. 3 and 4 show a comparison of the LHCb results [21] with results obtained by the CDF [28] and CMS [31] collaborations for the HX and CS frames, respectively. There is good agreement with CMS results for both frames, and with CDF for the CS frame.

The LHCb collaboration continues to perform measurements devoted to $b$-hadron and quarkonium physics [49, 50, 51, 52]. In particular, the polarization studies performed by LHCb [11, 12, 21] allowed one to shed some new facts on production mechanism of heavy quarkonium states, and to aggravate old ones.

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Figure 2: The measured values of $\lambda_\theta, \lambda_\phi$ for a) $\Upsilon(1S)$, b) $\Upsilon(2S)$ and c) $\Upsilon(3S)$ mesons. The red solid circles, blue open squares and green solid diamonds correspond to the helicity (HX), Collins-Soper (CS) and Gottfried-Jackson (GJ) frames, respectively. The thick black lines show the regions allowed by the positivity constraints.

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bars indicate the sum of the statistical and systematic uncertainties added in quadrature.

green open diamonds. Some data points are displaced from the bin centers to improve visibility. The error
the CDF collaboration [28] in p

The values of \( \lambda_0 \) (top), \( \lambda_{0\phi} \) (middle) and \( \lambda_{\phi} \) (bottom) parameters, measured in the HX frame
for \( \Upsilon(1S) \) (left), \( \Upsilon(2S) \) (center) and \( \Upsilon(3S) \) (right) mesons. Results of the LHCb analysis for the
rapidity region \( 2.2 < y^T < 4.5 \) are shown with red solid circles and blue solid squares for data collected
in pp collisions at \( \sqrt{s} = 7 \) and 8 TeV, respectively. The results by the CMS collaboration [31] obtained
in pp collision at \( \sqrt{s} = 7 \) TeV for rapidity regions \( |y^T| < 0.6 \) and \( 0.6 < |y^T| < 1.2 \) are shown with magenta open upward triangles and cyan open downward triangles, respectively. The results obtained by
the CDF collaboration [28] in pp collision at \( \sqrt{s} = 1.96 \) TeV for rapidity region \( |y^T| < 0.6 \) are shown with
green open diamonds. Some data points are displaced from the bin centers to improve visibility. The error
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Figure 4: The values of $\lambda_\theta$ (top), $\lambda_\theta\phi$ (middle) and $\lambda_\phi$ (bottom) parameters, measured in the CS frame for $\Upsilon(1S)$ (left), $\Upsilon(2S)$ (center) and $\Upsilon(3S)$ (right) mesons. Results of the LHCb analysis for the rapidity region $2.2 < y_{\Upsilon} < 4.5$ are shown with red solid circles and blue solid squares for data collected in pp collisions at $\sqrt{s} = 7$ and 8 TeV, respectively. The results by the CMS collaboration [31] obtained in pp collision at $\sqrt{s} = 7$ TeV for rapidity regions $|y_{\Upsilon}| < 0.6$ and $0.6 < |y_{\Upsilon}| < 1.2$ are shown with magenta open upward triangles and cyan open downward triangles, respectively. The results obtained by the CDF collaboration [28] in p$\bar{p}$ collision at $\sqrt{s} = 1.96$ TeV for rapidity region $|y_{\Upsilon}| < 0.6$ are shown with green open diamonds. Some data points are displaced from the bin centers to improve visibility. The error bars indicate the sum of the statistical and systematic uncertainties added in quadrature.