Polarization measurements at LHCb

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On behalf of LHCb Collaboration

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Outline

- Introduction
- LHCb detector
- $J/\psi (1S)$ polarization results
- $\psi (2S)$ polarization results
- $\Upsilon (nS)$ polarization results (arXiv:1709.01301)  
  new!
- Summary
**Introduction**

- **Mechanism of heavy quarkonium production is a long-standing problem in QCD**

- **Color Evaporation Model (CEM):** reasonable agreement with most of the measured quarkonia cross sections but “no predictive power for the polarization”

- **Color Singlet Model (CSM):** NNLO* calculations reduces the gap between data and CSM predictions but: 1) at LO predicts transverse polarization for S-wave quarkonia: $J/\psi(1S), \psi(2S), \Upsilon(nS)$; 2) at NLO predicts longitudinal polarization; 3) convergence of next order calculations ($N^3$LO and etc)?

- **Nonrelativistic QCD factorization approach (NRQCD):** includes CS and CO components, good agreement with the measured quarkonia cross sections, predicts transverse polarization for S-wave quarkonium states
Feed-down component: $\Upsilon(3S)$ from $\chi_b$ decays

Fraction of $\Upsilon(3S)$ mesons coming from $\chi_b(3P)$ states is around 40% (LHCb, 2014). Previously, this feed-down was ignored in calculations.
Introduction: differential xsec for $\Upsilon(nS)$

Full NLO NRQCD calculations of $p_T$ spectra

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Introduction

CMS polarization analysis: pp collisions, √s = 7 TeV, full angular distribution analysis for the Υ(nS) states in (10 < p_T < 50 GeV/c) & (|y| < 0.6) & (0.6 < |y| < 1.2), observed no significant Υ polarization

LHCb polarization results (2017): pp collisions, √s = 7 & 8 TeV, full angular distribution analysis for the Υ(nS) states in the complementary kinematical region (0 < p_T < 30 GeV/c) & (2.2 < y < 4.5), new polarization analysis (arXiv:1709.01301)

CDF polarization analysis: ¯p p collisions, √s = 1.96 TeV, the 1st full angular distribution analysis (determination of all the three λ parameters) for Υ(nS) in (0 < p_T < 40 GeV/c) & (|y| < 0.6). Performed the 1st measurement of the Υ(3S) polarization. CDF results (2012) consistent with their previous measurement (2002), but inconsistent with the D0 results (2008) for the Υ(1S) polarization. No large polarization is observed

Figure: Υ(nS) polarization results obtained by CDF (2012) and CMS (2012) collaborations.
Introduction (polarization frames)

Angular distribution for the dileptons from the decay of vector particles (for parity-invariant processes)

\[ \frac{d^2 N}{d \cos \theta \, d\phi} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_{\theta \phi} \sin 2\theta \cos \phi + \lambda_\phi \sin^2 \theta \cos 2\phi \]

Transverse (longitudinal) polarization: \( \lambda_\theta > 0 \) (\( \lambda_\theta < 0 \))

Helicity (HX) frame: the z axis is along the 3-momentum of \( \Upsilon \) in the cms of the colliding hadrons,

Collins-Soper (CS) frame: direction of the difference between velocity vectors of the colliding hadrons,

Gottfried-Jackson (GJ) frame: direction of one of the two colliding hadrons in the \( \Upsilon \) rest frame

\[ \lambda_{\text{inv}} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi} \quad \text{frame-invariant quantity,} \quad \text{Teryaev, Proceedings of Dubna-Spin-05, (2005)} \]

\[ \text{Faccioli et al., PR D81 (2010) 111502} \]
2 < \eta < 5
4% of solid angle
40% of heavy quarks

The LHCb detector
is a single-arm forward spectrometer designed for precision studies of b- and c-hadrons

Prompt $J/\psi$ polarization @ $\sqrt{s} = 7$ TeV

$J/\psi$ polarization: pp collisions @ $\sqrt{s} = 7$ TeV, $\mathcal{L} = 0.37$ fb$^{-1}$ (1st half of 2011) $p_T \in [2, 3, 4, 5, 7, 10, 15]$ GeV/c, $y \in [2.0, 2.5, 3.0, 3.5, 4.0, 4.5]$, only prompt $J/\psi$ mesons
$J/\psi$ polarization @ $\sqrt{s} = 7$ TeV
All calculations are at NLO. No agreement with theoretical model predictions. Different NRQCD calculations use different LDMEs.
$\psi (2S)$ polarization @ $\sqrt{s} = 7$ TeV

$\psi (2S)$ polarization: pp collisions @ $\sqrt{s} = 7$ TeV,
\[ \mathcal{L} = 1 \text{ fb}^{-1} (2011), \quad p_T \in [3.5, 4, 5, 7, 10, 15] \text{ GeV/c}, \]
\[ y \in [2.0, 2.5, 3.0, 3.5, 4.0, 4.5] \]
$$\psi (2S) \text{ polarization } @ \sqrt{s} = 7 \text{ TeV}$$

No significant polarization is observed

$\lambda_{\text{inv}}$ shows small negative polarization

In good agreement with CMS results

(PL B727 (2013) 381)
$\psi(2S)$ polarization @ $\sqrt{s} = 7$ TeV

Some agreement with NRQCD at low $p_T$ but don't support large transverse polarization at high $p_T$
$Y(nS)$ polarization (new!) 

arXiv:1709.01301
100th anniversary of the Russian Revolution (1917)

40th anniversary of the b revolution: discovery of the b quark (1977)
PRL 39 (1977) 252
Datasets and Selection

The same selection requirements as in the previous LHCb analyses:
\( \Upsilon(nS) \) @ 2.76 TeV EPJ C74 (2014) 2835, \( \Upsilon(nS) \) @ 7 & 8 TeV JHEP 1511 (2015) 103
with two additional cuts: \( \eta_\mu > 2.2 \), \( |\cos \theta_{GJ}| < 0.8 \)

\( \Upsilon(nS) \) signal extraction is done by unbinned extended maximum likelihood fit based on sPlot technique. In each (\( p_T, y \)) bin, the dimuon mass distribution is described by sum of three Crystal Ball functions (for 3 signal components), and exponential function (for combinatorial background)

\[
\sqrt{s} = 7 \text{ TeV}, \mathcal{L} = 1 \text{ fb}^{-1} (2011), \text{ pp collisions} \\
\sqrt{s} = 8 \text{ TeV}, \mathcal{L} = 2 \text{ fb}^{-1} (2012), \text{ pp collisions} \\
\Upsilon(nS) \text{ reconstructed in } \mu^+\mu^- \text{ decay mode} \\
fiducial volume: (2.2 < y < 4.5) \& (p_T < 30 \text{ GeV/c}) \\
p_T \in [0, 2, 4, 6, 8, 10, 15, 20, 30] \text{ GeV/c} \\
y \in [2.2, 3.0, 3.5, 4.5] \\
<\sigma_M> = 42 \text{ MeV/c}^2 – mass resolution
Analysis strategy

- In each \((p_T, y)\) bin, fit dimuon mass and extract \(Y(nS)\) candidates using sPlot technique.
- In each \((p_T, y)\) bin, perform 2D fit of \((\cos \theta, \phi)\) distributions using sFit technique.
- The \(\lambda\)-parameters are determined in three polarization frames: helicity (HX), Collin-Soper (CS) and Gottfried-Jackson (GJ), in different \((p_T, y)\) bins of the \(Y(nS)\).
- Perform 522 sFits: \((2 \text{ years}) \times (3 \text{ \(Y\) states}) \times (3 \text{ frames}) \times (7 \times 3 + 8 \times 1 \text{ bins})\)

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

arXiv:1709.01301
Analysis strategy

The measurement of $\lambda$-parameters is done by the unbinned maximum likelihood approach (sFit method) successfully applied in the LHCb polarization analysis of the $J/\psi$ and $\psi(2S)$ mesons:

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

$(\cos \theta_i, \phi_i)$ – angular variables of $\mu^+$ in the $\Upsilon$ rest frame for an $i^{th}$ $\Upsilon$ candidate in data;

$\varepsilon(\cos \theta_i, \phi_i)$ – total efficiency; $\mathcal{N}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$ – normalization of the numerator determined by MC;

$$\mathcal{P}(\cos \theta_i, \phi_i|\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \equiv 1 + \lambda_\theta \cos^2 \theta_i + \lambda_{\theta\phi} \sin 2\theta_i \cos \phi_i + \lambda_\phi \sin^2 \theta_i \cos 2\phi_i$$

$w_i^{\Upsilon(nS)}$ – sWeights to subtract background using sPlot analysis ($m_{\mu\mu}$ as control variable);

$$s_w = \frac{\sum_{i=1}^{N_{\text{tot}}} w_i^{\Upsilon(nS)}}{\left( \sum_{i=1}^{N_{\text{tot}}} (w_i^{\Upsilon(nS)})^2 \right)^{1/2}}$$ – scale factor to determine correctly statistical uncertainties

arXiv:1709.01301
**sFit example**

\[ \lambda_\theta = 0.069 \pm 0.045 \]
\[ \lambda_{\theta\phi} = -0.069 \pm 0.019 \]
\[ \lambda_\phi = -0.006 \pm 0.009 \]
\[ \bar{\lambda} = 0.050 \pm 0.057 \]

**HX frame**

\[ \lambda_\theta = 0.139 \pm 0.052 \]
\[ \lambda_{\theta\phi} = 0.002 \pm 0.017 \]
\[ \lambda_\phi = -0.026 \pm 0.007 \]
\[ \bar{\lambda} = 0.059 \pm 0.058 \]

**CS frame**

\[ \lambda_\theta = 0.065 \pm 0.033 \]
\[ \lambda_{\theta\phi} = 0.066 \pm 0.024 \]
\[ \lambda_\phi = -0.005 \pm 0.013 \]
\[ \bar{\lambda} = 0.048 \pm 0.058 \]

**GJ frame**

\[ \gamma(1S) \text{ polarization results for } (4 < p_T < 6 \text{ GeV/c}) \& (2.2 < y < 3.0) @ \sqrt{s} = 7 \text{ TeV} \]

\[ \tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi} \]

*frame-invariant quantity*
## Summary of systematic uncertainty

**Statistical uncertainty dominates over systematic uncertainty**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\lambda_\theta \times 10^{-3}$</th>
<th>$\lambda_{\theta\phi} \times 10^{-3}$</th>
<th>$\lambda_\phi \times 10^{-3}$</th>
<th>$\bar{\lambda} \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$\Upsilon(1S)$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimuon mass fit</td>
<td>$1.0 - 12$</td>
<td>$0.2 - 10$</td>
<td>$0.1 - 7$</td>
<td>$1.8 - 20$</td>
</tr>
<tr>
<td>Efficiency calculation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>muon identification</td>
<td>$0.2 - 10$</td>
<td>$0.1 - 7$</td>
<td>$0.1 - 6$</td>
<td>$0.2 - 17$</td>
</tr>
<tr>
<td>correction factors for $e^{\mu^+\mu^-}$</td>
<td>$0.7 - 12$</td>
<td>$0.4 - 5$</td>
<td>$0.1 - 4$</td>
<td>$2.1 - 14$</td>
</tr>
<tr>
<td>trigger</td>
<td>$0.1 - 18$</td>
<td>$0.1 - 8$</td>
<td>$0.1 - 5$</td>
<td>$0.3 - 19$</td>
</tr>
<tr>
<td>Finite size of simulated samples</td>
<td>$6.0 - 82$</td>
<td>$1.3 - 29$</td>
<td>$0.9 - 35$</td>
<td>$6.9 - 95$</td>
</tr>
<tr>
<td><strong>$\Upsilon(2S)$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimuon mass fit</td>
<td>$0.6 - 37$</td>
<td>$0.2 - 19$</td>
<td>$0.3 - 16$</td>
<td>$4.6 - 53$</td>
</tr>
<tr>
<td>Efficiency calculation</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>muon identification</td>
<td>$0.2 - 11$</td>
<td>$0.1 - 6$</td>
<td>$0.1 - 5$</td>
<td>$0.2 - 13$</td>
</tr>
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<td>$0.3 - 5$</td>
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<td>$0.1 - 7$</td>
<td>$0.1 - 5$</td>
<td>$0.3 - 18$</td>
</tr>
<tr>
<td>Finite size of simulated samples</td>
<td>$9.8 - 214$</td>
<td>$2.5 - 98$</td>
<td>$1.5 - 121$</td>
<td>$13.8 - 322$</td>
</tr>
<tr>
<td><strong>$\Upsilon(3S)$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimuon mass fit model</td>
<td>$1.4 - 72$</td>
<td>$0.2 - 24$</td>
<td>$0.5 - 21$</td>
<td>$7.2 - 86$</td>
</tr>
<tr>
<td>Efficiency calculation</td>
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<td>$2.1 - 18$</td>
</tr>
<tr>
<td>trigger</td>
<td>$0.2 - 17$</td>
<td>$0.1 - 8$</td>
<td>$0.1 - 4$</td>
<td>$0.3 - 19$</td>
</tr>
<tr>
<td>Finite size of simulated samples</td>
<td>$12.4 - 277$</td>
<td>$3.5 - 102$</td>
<td>$2.1 - 113$</td>
<td>$15.8 - 345$</td>
</tr>
</tbody>
</table>
$\Upsilon(1S)$ polarization in HX frame

LHCb 
$\sqrt{s} = 7$ TeV

LHCb 
$\sqrt{s} = 8$ TeV

$\Upsilon(1S)$
HX frame

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arXiv:1709.01301
$\Upsilon(2S)$ polarization in HX frame

arXiv:1709.01301
$\Upsilon(3S)$ polarization in HX frame

LHCb
$\sqrt{s} = 7\text{ TeV}$

LHCb
$\sqrt{s} = 8\text{ TeV}$

$\Upsilon(3S)$
HX frame

$2.2 < y_{\Upsilon} < 3.0$

$3.0 < y_{\Upsilon} < 3.5$

$3.5 < y_{\Upsilon} < 4.5$

$\lambda_y$

$\lambda_{\phi}$

$\lambda_{\epsilon}$

$\lambda_T$

$p_T^\Upsilon$ [GeV/c]
$\Upsilon(nS)$ polarization in HX frame ($2.2 < y < 4.5$)

arXiv:1709.01301
Positivity and other constraints

\[
\begin{align*}
0 \leq C_1 &= 1 - |\lambda_\theta| \\
0 \leq C_2 &= 1 + \lambda_\theta - 2|\lambda_\phi| \\
0 \leq C_3 &= (1 - \lambda_\theta)(1 + \lambda_\theta - 2\lambda_\phi) - 4\lambda_{\theta\phi}^2 \\
0 \leq C_4 &= (1 - \lambda_\theta)(1 + \lambda_\theta + 2\lambda_\phi) \\
0 \leq C_5 &= (1 + \lambda_\theta)^2 - 4\lambda_\phi^2 \\
0 \leq C_6 &= (1 + \lambda_\theta + 2\lambda_\phi)((1 - \lambda_\theta)(1 + \lambda_\theta - 2\lambda_\phi) - 4\lambda_{\theta\phi}^2)
\end{align*}
\]

- All the positivity constraints are satisfied
- The frames HX, CS and GJ coincide in the limit \( p_T \to 0 \) (satisfied)
- \( \lambda_{\theta\phi} \to 0 \) in the limit \( p_T \to 0 \) (Lam-Tung, 1978) (satisfied)
- \( \lambda_\phi \to 0 \) in the limit \( p_T \to 0 \) (Lam-Tung, 1978) (satisfied)
Comparison of LHCb, CMS and CDF results

arXiv:1709.01301

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Comparison of LHCb, CMS and CDF results

arXiv:1709.01301
Summary for the LHCb polarization results

- No agreement of the $J/\psi (1S)$ and $\psi (2S)$ polarization results with any theoretical model prediction
- No large polarizations are observed for the $\Upsilon(nS)$ mesons
- The parameters $\lambda_{\theta\phi}$ and $\lambda_{\phi}$ are small in all frames and in all kinematical ranges
- No clear dependence on rapidity is observed
- Good agreement in the LHCb polarization results between 7 and 8 TeV
- Good agreement between LHCb and CMS polarization results in all frames
- Good agreement between LHCb and CDF results in CS frame, but not in HX frame
Thank You
Backup
Full NLO NRQCD calculations of $\Upsilon(nS)$ polarization

Good description for $\Upsilon(1S)$ & $\Upsilon(2S)$ of CMS results, but not for $\Upsilon(3S)$ of CDF and CMS

Feed-down from $\chi_b$ is taken for $\Upsilon(1S)$ & $\Upsilon(2S)$, but not for $\Upsilon(3S)$
Analysis strategy (details)

- Perform angular distribution analysis of the $\Upsilon(nS) \rightarrow \mu^+\mu^-$ decay, i.e. we determine the angular distribution parameters $(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$ from

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

- The $\lambda$-parameters are determined in three polarization frames: helicity (HX), Collin-Soper (CS) and Gottfried-Jackson (GJ), in different bins of the $\Upsilon(nS)$ transverse momentum and rapidity:

  \[ \begin{align*}
  p_T^X & : [0.0, 2.0), [2.0, 4.0), [4.0, 6.0), [6.0, 8.0), [8.0, 10.0), [10.0, 15.0), [15.0, 20.0) \text{ GeV/c} \\
  y^X & : [2.2, 3.0), [3.0, 3.5), [3.5, 4.5). 
  \end{align*} \]

- The measurement of $\lambda$-parameters is done by the unbinned maximum likelihood approach (sFit method) successfully applied in the LHCb polarization analysis of the $J/\psi$ and $\psi(2S)$ mesons:

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

  - $(\cos \theta_i, \phi_i)$ – angular variables of $\mu^+$ in the $\Upsilon$ rest frame for an $i^{th}$ $\Upsilon$ candidate in data;
  - $\varepsilon(\cos \theta_i, \phi_i)$ – total efficiency; $\mathcal{N}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$ – normalization of the numerator determined by MC;
  - $\mathcal{P}(\cos \theta_i, \phi_i | \lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \equiv 1 + \lambda_\theta \cos^2 \theta_i + \lambda_{\theta\phi} \sin 2\theta_i \cos \phi_i + \lambda_\phi \sin^2 \theta_i \cos 2\phi_i$;
  - $w_i^{\Upsilon(nS)}$ – sWeights to subtract background using sPlot analysis ($m_{\mu\mu}$ as control variable);
  - $s_w = \sum_{i=1}^{N_{\text{tot}}} w_i^{\Upsilon(nS)} / \left( \sum_{i=1}^{N_{\text{tot}}} (w_i^{\Upsilon(nS)})^2 \right)^{1/2}$ – scale factor to determine correctly statistical uncertainties.
Sources of systematic uncertainty

- Related to the extraction of the $Y(nS)$ signals:
  a) variation of signal and background parametrization
  b) fix/release constraints imposed in the mass fit model

- Related to the muon ID efficiency

- Related to the muon ID correction

- Related to the track reconstruction efficiency

- Related to the trigger requirements

- Related to the finite size of MC samples:
  this source is the largest at high $p_T$ but stat. uncertainty dominates over syst. uncertainty