Measurements of Quarkonium Polarization with the CMS Experiment

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on behalf of the
CMS Collaboration

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Outline

- Motivation
- Basic polarization concepts
- CMS $\Upsilon(nS)$ polarization analysis
- Systematic uncertainties
- Polarization results
Motivation

- After decades of theoretical and experimental progress, quarkonium production is still not well understood.
- Quarkonium polarization is a powerful observable with the possibility of discriminating between various theoretical models.
- New measurements needed, especially for the $\Upsilon$ family and high $p_T$.

![Graph showing $\lambda_\theta$ vs $p_T$ for $J/\psi$, $|y| < 0.6$.]
Quarkonium Polarization

- Polarization is measured through the average angular decay distribution, most generally written as

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

where \(\lambda_\theta\), \(\lambda_\phi\), \(\lambda_{\theta\phi}\) are the polarization parameters

- Two extreme angular decay distributions:

  **Longitudinal polarization**  
  \(J_z = 0\)
  \(\lambda_\theta = -1\)
  \(\lambda_\phi = 0\)
  \(\lambda_{\theta\phi} = 0\)

  **Transverse polarization**  
  \(J_z = \pm 1\)
  \(\lambda_\theta = +1\)
  \(\lambda_\phi = 0\)
  \(\lambda_{\theta\phi} = 0\)
Definitions

- Angular decay distribution measured with respect to a certain reference frame:
  - center-of-mass helicity $H_X$ (polar axis $z_{HX} \approx$ direction of quarkonium momentum)
  - Collins-Soper CS ($z_{CS} \approx$ direction of relative velocity of colliding particles)
  - perpendicular helicity $P_X$ ($z_{PX} \perp z_{CS}$)
- Usage of the dimuon decay channel $\Upsilon(nS) \rightarrow \mu^+\mu^-$
Need to Measure Full Angular Distribution

- Measure the full angular decay distribution (three polarization parameters): Two very different physical cases are indistinguishable if only $\lambda_\theta$ is measured.
- Observed polarization depends on the frame

\[
\begin{align*}
\lambda_\theta &= +1 \\
\lambda_\phi &= -1
\end{align*}
\]

\[
\begin{align*}
\lambda_\theta &= -1 \\
\lambda_\phi &= 0
\end{align*}
\]
Define frame invariant parameters such as $\tilde{\lambda}$ from the angular decay distribution of a given frame

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

CMS Detector
Three polarization parameters $\lambda_\theta$, $\lambda_\Phi$, $\lambda_{\theta \Phi}$ and the frame invariant parameter $\tilde{\lambda}$ are measured in three different reference frames (PX, CS, HX) for inclusive $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$.

Fully data-driven analysis based on dimuon sample collected in pp collisions in 2011 at $\sqrt{s} = 7$ TeV, corresponding to a total integrated luminosity of 4.9 fb$^{-1}$.

Estimated number of signal events in the kinematic phase space under consideration ($p_T > 10$ GeV, $|y| < 1.2$):

<table>
<thead>
<tr>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>222k</td>
<td>82k</td>
<td>51k</td>
</tr>
</tbody>
</table>

Analysis performed independently in five transverse momentum $p_T$ bins for two dimuon rapidity $|y|$ cells.
Obtaining Polarization Parameters

Full and direct calculation of the Posterior Probability Distribution (PPD) of the polarization parameters $\lambda_\theta$, $\lambda_\phi$, $\lambda_{\theta\phi}$

1. Events distributed as in the background model are subtracted from the data sample
2. Definition of the PPD from the remaining signal-like events
3. Numerical results and graphical representations are determined from 1D and 2D projections of the PPD

$\Upsilon(1S)$ $|y| < 0.6$ $30 < p_T < 50$ GeV
Background Subtraction

- Signal region is defined as ±1σ around mass peak
- Background fraction is determined by fits to the dimuon mass distribution
- Angular distribution of the background events are modeled as weighted sums of the distributions in the sidebands, left of Υ(1S) and right of Υ(3S) peak
- Event-by-event background subtraction of background-like events using a likelihood ratio criterion
Efficiencies

- Data-driven single muon efficiencies measured with the Tag&Probe method
- Precise knowledge of efficiencies needed to avoid introducing artificial polarization
- Dimuon efficiencies are calculated as the product of single muon efficiencies
- Correlations between muons are negligible as shown in detailed MC studies
- Efficiencies are accounted for on an event-by-event basis
Systematic Effects

- Sources of systematic effects:
  - Analysis method
  - Background model
  - Muon efficiencies

- Systematic uncertainties are propagated to the PPD

- Total uncertainties of the measurements are dominated by systematics at low $p_T$ and statistics at high $p_T$

- $\Upsilon(2S)$ and $\Upsilon(3S)$ systematic uncertainties are dominated by the background model uncertainty, especially at low $p_T$
$\Upsilon(nS)$ Polarization in the HX Frame, $|y| < 0.6$

CMS pp, $\sqrt{s} = 7$ TeV, $L = 4.9$ fb$^{-1}$ preliminary

$\lambda_\theta$

$\lambda_\phi$

$\lambda_{\theta\phi}$

$Y(1S)$ $Y(2S)$ $Y(3S)$ $Y(1S)$ $Y(2S)$ $Y(3S)$

Stat. uncert., 68.3 % CL
Tot. uncert., 68.3 % CL
Tot. uncert., 95.5 % CL
Tot. uncert., 99.7 % CL

$\Upsilon(nS)$ Polarization in the HX Frame, $0.6 < |y| < 1.2$

CMS $pp \sqrt{s} = 7$ TeV $L = 4.9 fb^{-1}$
preliminary

$\lambda_\theta$

$\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$

$\lambda_\phi$

$\lambda_{\theta\phi}$

$\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$

Frame Invariant Parameter $\tilde{\lambda}$

- Results of all three reference frames are consistent
- No evidence of unaccounted systematic uncertainties
Summary and Conclusions

- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarizations in pp collisions at 7 TeV have been determined, using the dimuon data collected by CMS in 2011, corresponding to an integrated luminosity of 4.9 fb$^{-1}$

- Three frame dependent anisotropy parameters $\lambda_\theta$, $\lambda_\Phi$, $\lambda_{\theta\Phi}$ in three different polarization frames (CS, HX, PX) as well as the frame invariant parameter $\tilde{\lambda}$ have been measured

- Results were obtained in five $p_T$ bins for two $|y|$ ranges, covering the kinematic region of $10 < p_T < 50$ GeV and $|y| < 1.2$

- No strong longitudinal or transverse polarizations have been observed
Y(nS) Polarization in the PX Frame, |y| < 0.6
$Y(nS)$ Polarization in the PX Frame, $0.6 < |y| < 1.2$

CMS $pp$, $\sqrt{s} = 7$ TeV, $L = 4.9$ fb$^{-1}$

preliminary

Stat. uncert., 68.3 % CL
Tot. uncert., 68.3 % CL
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$p_T$ [GeV]

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Y(nS) Polarization in the CS Frame, |y| < 0.6

CMS pp $\sqrt{s} = 7$ TeV $L = 4.9$ fb$^{-1}$
preliminary

Stat. uncert., 68.3 % CL
Tot. uncert., 68.3 % CL
Tot. uncert., 95.5 % CL
Tot. uncert., 99.7 % CL

p$_{T}$ [GeV] 10 15 20 25 30 35 40 45

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Y(nS) Polarization in the CS Frame, $0.6 < |y| < 1.2$

CMS pp $\sqrt{s} = 7$ TeV $L = 4.9$ fb$^{-1}$

preliminary

$\lambda_{\theta}$

$\lambda_{\phi}$

$\lambda_{\theta\phi}$

Stat. uncert., 68.3 % CL

Tot. uncert., 68.3 % CL

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Definition of the PPD

\[ \mathcal{P}(\vec{\lambda}) \propto \prod_i \frac{1}{\mathcal{N}(\vec{\lambda})} \ K(p_T^{(i)}, y^{(i)}, M^{(i)}) \ W(\cos \theta^{(i)}, \phi^{(i)} | \vec{\lambda}) \ \varepsilon(p_1^{(i)}, p_2^{(i)}) \]

\( \mathcal{N} \): normalization

K: event distribution in the bin, previously determined from the data

W: general angular distribution

\( \varepsilon \): dimuon efficiency as a function of the muon momenta