Measurements of Quarkonium Production and Polarization at CMS

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Outline

- $\Upsilon(nS)$ cross section
- $\Upsilon(nS)$ polarization
- Prompt $J/\psi$ polarization
- Prompt $\psi(2S)$ polarization

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

- No theory has simultaneously explained experimental measurements of both quarkonium production and polarization
- Most previous polarization measurements only determined one out of three polarization parameters
- CMS has a higher reach in transverse momentum, $p_T$
Y(nS) Cross Section Analysis

- Uses results from CMS Y(nS) polarization measurement for the calculation of the acceptance
- Kinematic range of measurement: $10 < p_T < 100$ GeV, $|y| < 0.6$

Details in CMS-PAS-BPH-12-006
**ϒ(nS) Differential Cross Section**

- ϒ(nS) differential cross section \( \frac{d\sigma}{dp_T} \) times dimuon branching ratio \( B \)
  integrated over \( |y| < 0.6 \) in a given \( p_T \) bin of width \( \Delta p_T \)

\[
\frac{d\sigma(pp \rightarrow \Upsilon(nS))}{dp_T} \bigg|_{y<0.6} \times B(\Upsilon(nS) \rightarrow \mu^+\mu^-) = \frac{N_{\Upsilon(nS)}^{fit}(p_T)}{L_{int} \cdot \Delta p_T \cdot \varepsilon(p_T) \cdot A(p_T)}
\]

- \( N_{\Upsilon(nS)}^{fit}(p_T) \) number of \( \Upsilon(nS) \) events in a \( p_T \) bin of width \( \Delta p_T \)
- \( L_{int} \) integrated luminosity (4.9 fb\(^{-1}\))
- \( \varepsilon(p_T) \) efficiency of trigger, reconstruction and analysis selections
- \( A(p_T) \) acceptance calculated from Monte Carlo

- Acceptance is the polarization-weighted fraction of \( \Upsilon \) decays where the muons satisfy the kinematic requirements to the total of weighted events in a given \( p_T, y \) bin
• Similar behaviour for all three Υ states
• Change of slope for $p_T > 20$ GeV suggests a change in the nature of the production process
Polarization is measured through the average angular decay distribution - for vector particles most generally written as

\[ W(\cos \vartheta, \varphi | \vec{\lambda}) = \frac{3/(4\pi)}{(3 + \lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2 \vartheta + \lambda_\varphi \sin^2 \vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi) \]

where \( \lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi} \) are the polarization parameters

Angular decay distribution is measured with respect to a certain reference frame

- center-of-mass helicity \( H_X \) (polar axis \( z_{HX} \) ≈ direction of quarkonium momentum)
- Collins-Soper CS (\( z_{CS} \) ≈ direction of relative velocity of colliding particles)
- perpendicular helicity \( P_X \) (\( z_{PX} \perp z_{CS} \))
Need to Measure the Full Angular Distribution

- Two extreme angular decay distributions
  
  Longitudinal polarization $J_z = 0$
  
  \[ \lambda_\theta = -1 \]
  \[ \lambda_\varphi = 0 \]
  \[ \lambda_{\theta\varphi} = 0 \]

  Transverse polarization $J_z = \pm 1$
  
  \[ \lambda_\theta = +1 \]
  \[ \lambda_\varphi = 0 \]
  \[ \lambda_{\theta\varphi} = 0 \]

- The full angular distribution has to be measured. Otherwise two very different physical cases cannot be distinguished.

- The shape of the distribution is invariant and can be characterized by the frame invariant parameter $\tilde{\lambda} = (\lambda_\theta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$
• $\lambda_\theta$, $\lambda_\phi$, $\lambda_{\theta\phi}$ and $\tilde{\lambda}$ are measured in three different reference frames (HX, CS, PX) for $J/\psi$, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons.

• As a function of transverse momentum $p_T$
  - $J/\psi$: $14 < p_T < 70$ GeV (10 bins)
  - $\psi(2S)$: $14 < p_T < 50$ GeV (4 bins)
  - $\Upsilon(nS)$: $10 < p_T < 50$ GeV (5 bins)

• And dimuon rapidity, $|y|$
  - $J/\psi$, $\Upsilon(nS)$: $|y| < 1.2$ (2 bins)
  - $\psi(2S)$: $|y| < 1.5$ (3 bins)

• An additional non prompt component has to be taken into account for $\psi(nS)$ states

Details in PRL 110, 081802 (2013) and CMS-PAS-BPH-13-003
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 until the previously determined background fraction is reached
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

\[ \lambda_\theta, \lambda_\phi, \lambda_{\theta\phi} \]
Systematic Effects

- **Sources of systematic effects:**
  - Extraction of polarization parameters
  - Background model
  - Muon efficiencies

- **Systematic uncertainties are propagated to the PPD**

- **Good agreement between the $\tilde{\lambda}$ parameters in the three reference frames shows no indication of unaccounted systematic uncertainties**

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**Figure:**

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

- **Legend:**
  - CS
  - HX
  - PX

- **Axes:**
  - $\tilde{\lambda}$ vs. $p_T$ [GeV]
  - $J/\psi$ $|y| < 0.6$
  - $\psi(2S)$ $|y| < 0.6$

- **Legend:**
  - Total uncertainty at 68.3% CL
Y(nS) Polarization in the HX Frame, |y| < 0.6
**ϒ(nS): Comparison to NLO NRQCD**

- Theory calculation accounts for feed-down contributions to \( \Upsilon(1S) \) and \( \Upsilon(2S) \) states
- Prediction for \( \Upsilon(3S) \) may change when including feed-down from \( \chi_b \) (3P) states
- Color octet matrix elements are fit to hadroproduction data only
Prompt \( \psi(nS) \) Polarization in the HX Frame

- No sign of strong polarization
- \( \psi(2S) \) is not affected by feed-down decays from higher states

Error bars show total uncertainties at 68.3% CL
**ψ(nS): Comparison to NLO NRQCD**

- CMS results disagree with the NLO NRQCD calculations
- Calculations use a global fit of color octet matrix elements to photo- as well as hadroproduction data
- Theory predicts polarization only for directly produced J/ψ’s

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**ψ(1S)**

- **pp √s = 7 TeV**
- **HX frame**
- |y| < 0.6

**ψ(2S)**

- **pp √s = 7 TeV**
- **HX frame**
- |y| < 0.6

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CMS Preliminary, L = 4.9 fb⁻¹, total uncert. 68.3% CL

Summary and Conclusions

- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ differential cross sections for $10 < p_T < 100$ GeV are measured using CMS polarization results.

- A change in the slope of the differential cross sections from an exponential to power-law is observed.

- Frame dependent polarization parameters $\lambda_\theta$, $\lambda_\phi$, $\lambda_{\theta\phi}$ and the frame invariant parameter $\bar{\lambda}$ are measured in three different frames (CS, HX, PX) for the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and prompt $J/\psi$ and $\psi(2S)$ mesons.

- $J/\psi$ results are shown for the first time.

- No evidence of strong longitudinal or transverse polarizations has been observed.

- $J/\psi$ and $\psi(2S)$ measurements are in disagreement with current theoretical predictions.
CMS Detector

Total weight: 12500 T
Overall diameter: 15.0 m
Overall length: 21.5 m
Magnetic field: 4 Tesla
Quarkonium Production
Line Shape Determination

- Mass PDF was defined with the help of radiative line shape determined from Monte Carlo and the mass resolution

\[
\mathcal{F}(M_{\mu\mu}; c_w, \delta m) = \frac{1}{N} \sum_{i=1}^{N} \frac{1}{\sqrt{2\pi c_w \zeta_i}} e^{-\frac{(M_{\mu\mu} - m_i - \delta m)^2}{2c_w^2 \zeta_i^2}}
\]

- \(c_w\) width scale factor
- \(\delta m\) mass shift scale factor
- \(m_i\) was sampled from the final-state radiation mass shape
- \(\zeta\) approximates the detector effects on the mass error
Dimuon Mass Fits

CMS Preliminary
$pp \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 4.9 \text{ fb}^{-1}$

$|y(\mu\mu)| < 0.6, 10 < p_{T}(\mu\mu) < 12 \text{ GeV}$

$|y(\mu\mu)| < 0.6, 38 < p_{T}(\mu\mu) < 40 \text{ GeV}$

$|y(\mu\mu)| < 0.6, 49 < p_{T}(\mu\mu) < 54 \text{ GeV}$

$|y(\mu\mu)| < 0.6, 70 < p_{T}(\mu\mu) < 100 \text{ GeV}$
Comparison to ATLAS and Previous CMS Measurements

CMS Preliminary
pp $\sqrt{s} = 7$ TeV, $L_{\text{int}} = 4.9$ fb$^{-1}$

ATLAS points normalized to
CMS $40 < p_T(\mu\mu) < 50$ GeV
luminosity unc. (4%) excluded

CMS 2011 $|y(\mu\mu)| < 0.6$

CMS 2011 $|y(\mu\mu)| < 1.2$, 1.8 fb$^{-1}$

ATLAS 2011 $|y(\mu\mu)| < 2.4 \times 0.25$, 36 pb$^{-1}$

CMS Preliminary
pp $\sqrt{s} = 7$ TeV, $L_{\text{int}} = 4.9$ fb$^{-1}$

luminosity unc. (4%) excluded

CMS Preliminary
pp $\sqrt{s} = 7$ TeV, $L_{\text{int}} = 4.9$ fb$^{-1}$

Y(1S)

Y(2S)$\times 0.1$

Y(3S)$\times 0.01$
Quarkonium Polarization
Contributions to the $\psi(nS)$ Prompt Signal Region

- The prompt-signal region is defined as a 2D window of $\pm 3\sigma$ widths in dimuon mass and (pseudo-proper) lifetime.
Definition of the PPD

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

\(\mathcal{N}\): normalization

\(W\): general angular distribution

\(\varepsilon\): dimuon efficiency as a function of the muon momenta
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 seen in detailed MC studies
- Efficiencies are accounted for on an event-by-event basis

![Efficiency Graph]

CMS pp $\sqrt{s} = 7$ TeV

- $|\eta(\mu)| < 0.2$
- $0.8 < |\eta(\mu)| < 1.0$
- $1.4 < |\eta(\mu)| < 1.6$
Frame Invariant Parameter $\tilde{\lambda}$

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

- $\Upsilon(1S)$, $|y| < 0.6$
- $\Upsilon(2S)$, $|y| < 0.6$
- $\Upsilon(3S)$, $|y| < 0.6$

- $\Upsilon(1S)$, $0.6 < |y| < 1.2$
- $\Upsilon(2S)$, $0.6 < |y| < 1.2$
- $\Upsilon(3S)$, $0.6 < |y| < 1.2$

- Statistical uncertainty, 68.3% CL, 68.3% CL
- Total uncertainty, 68.3% CL, 95.5% CL, 99.7% CL

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

- Total uncertainty at 68.3% CL

- $J/\psi$ $0.6 < |y| < 1.2$
- $\psi(2S)$ $0.6 < |y| < 1.2$
**Y(nS) Polarization in the HX Frame, 0.6 < |y| < 1.2**

- **CMS** pp $\sqrt{s} = 7$ TeV $L = 4.9$ fb$^{-1}$
- **HX frame, 0.6 < |y| < 1.2**

- $\lambda_\phi$ vs. $p_T$ for $Y(1S)$, $Y(2S)$, $Y(3S)$
- $\lambda_\varphi$ vs. $p_T$ for $Y(1S)$, $Y(2S)$, $Y(3S)$
- $\lambda_{\theta\varphi}$ vs. $p_T$ for $Y(1S)$, $Y(2S)$, $Y(3S)$

- Stat. uncert., 68.3 % CL
- Tot. uncert., 68.3 % CL
- Tot. uncert., 95.5 % CL
- Tot. uncert., 99.7 % CL
Y(nS) Polarization in the PX Frame, |y| < 0.6

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

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

$\lambda_\phi$

$\lambda_\psi$

$\lambda_\theta$
Y(nS) Polarization in the PX Frame, 0.6 < |y| < 1.2

CMS pp \(\sqrt{s} = 7 \text{ TeV} \) L = 4.9 fb\(^{-1}\) PX frame, 0.6 < |y| < 1.2

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

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

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

CS frame, |y| < 0.6

Stat. uncert., 68.3 % CL
Tot. uncert., 68.3 % CL
Tot. uncert., 95.5 % CL
Tot. uncert., 99.7 % CL
Y(nS) Polarization in the CS Frame, 0.6 < |y| < 1.2

CMS pp √s = 7 TeV L = 4.9 fb⁻¹

CS frame, 0.6 < |y| < 1.2

Stat. uncert., 68.3 % CL
Tot. uncert., 68.3 % CL
Tot. uncert., 95.5 % CL
Tot. uncert., 99.7 % CL
Prompt $\psi(nS)$ Polarization in the CS frame

CMS Preliminary CS frame

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

$\lambda_\phi$

Error bars show total uncertainties at 68.3% CL

$\lambda_\psi$

$\lambda_{\phi\psi}$

$p_T\ [\text{GeV}]$

$|y| < 0.6$

$0.6 < |y| < 1.2$

$1.2 < |y| < 1.5$
Prompt $\psi(nS)$ Polarization in the PX frame

Error bars show total uncertainties at 68.3% CL
ψ(1S): Comparison to NLO NRQCD

CMS, L = 4.9 fb⁻¹, total uncert. 68.3% CL


= 7 TeV

s

pp √s = 7 TeV

HX frame

|y| < 0.6

CMS, L = 4.9 fb⁻¹, total uncert. 68.3% CL


= 7 TeV

s

pp √s = 7 TeV

HX frame

|y| < 0.6

CMS, L = 4.9 fb⁻¹, total uncert. 68.3% CL


= 7 TeV

s

pp √s = 7 TeV

HX frame

0.6 < |y| < 1.2

CMS, L = 4.9 fb⁻¹, total uncert. 68.3% CL

$\psi(2S)$: Comparison to NLO NRQCD

CMS Preliminary, L = 4.9 fb$^{-1}$, total uncert. 68.3% CL