Measurements of Quarkonium production at CMS

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on Behalf of the CMS Collaboration
Motivations

- Heavy quarkonia are an excellent laboratory for understanding QCD
  - non-relativistic due to their high mass
  - nonperturbative effects can be simplified and constrained

- In the last decade, significant progress for production mechanisms
  - new experimental results
  - improved theoretical descriptions

- Definitive understanding still a challenge, several models competing for confirmation

- Renewed interest in quarkonium spectroscopy since the discovery of the XYZ exotic states:
  - search of new possible states
  - new measurements needed to understand their true nature
**CMS Quarkonium Studies**

**Y production cross section**
L\(_{\text{int}}\) = 3 pb\(^{-1}\)
*Phys. Rev. D 83, 112004 (2011)*

**Prompt and non-prompt J/ψ production**
L\(_{\text{int}}\) = 314 nb\(^{-1}\)

**J/ψ and ψ(2S) production**
L\(_{\text{int}}\) = 37 pb\(^{-1}\)
*JHEP 02, 011 (2012)*

**Observation of the χ\(_{c}\) states**
L\(_{\text{int}}\) = 1.1 fb\(^{-1}\)
*CERN-CMS-DP-2011-011*

**Measurement of the production cross section ratio of X(3872) and ψ(2S)**
L\(_{\text{int}}\) = 40 pb\(^{-1}\)
*CMS-PAS-BPH-10-018*

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Muons in CMS

- Quarkonium states identified in final states with di-muons

- Muon system information matched to an inner-tracker track for improved momentum resolution

- Inner Tracker:
  - Silicon pixel and strip layers
  - High $p_T$ resolution $\sim 1\%$
  - Excellent vertex reconstruction and impact parameter resolution

- Muon System
  - 3 types of gaseous detectors
  - Phase space coverage up to $|\eta| = 2.4$
  - Highly efficient muon trigger and identification
  - Resolution $\eta$ dependent.
Muon Triggers

2010 Run

Low instantaneous luminosity in 2010:
- Di-muon trigger without additional $p_T$ requirements
- Special triggers to collect very low $p_T$ muons in the first months

2011 Run Strategy

Higher instantaneous luminosity in 2011:
- Specific trigger paths developed for the different analyses
- High purity signal already at trigger level

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**S-wave quarkonium states**

- Unbinned Maximum Likelihood fit to $\mu^+\mu^-$ invariant mass distributions
- Signals modeled with Crystal Ball functions
- Mass differences are fixed from PDG, common resolution value (scaled by mass)
- Yields then corrected for Acceptance (from MC) and Efficiency (from data-driven methods)
  - muon acceptance is strongly dependent on production polarization

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**Data**

**CMS - $\sqrt{s} = 7$ TeV**

- $L = 37 \text{ pb}^{-1}$
- $|\eta^\mu| < 1.0$
- $8 < p_T < 9$ GeV/c
- $|y| < 1.2$

$\chi^2/\text{n.dof} = 94.4/99$

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**Graphs**

- **Barrel Region**
  - $\Upsilon(1S)$
  - $\Upsilon(2S)$
  - $\Upsilon(3S)$

- **Total**
  - $\Upsilon(1S)$
  - $\Upsilon(2S)$
  - $\Upsilon(3S)$

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Inclusive J/$\psi$ Production

\[ \frac{d^2\sigma}{dp_T dy} (J/\psi) \cdot B(J/\psi \rightarrow \mu^+\mu^-) = \frac{N^\text{corr}_{J/\psi}(p_T, |y|)}{\int L \, dt \cdot \Delta p_T \cdot \Delta y} \]

- Inclusive cross section comprises 3 production methods in hadron collisions:
  - **Prompt:**
    - Directly from pp collisions
    - “Feed-down” from heavier states as $\chi_c$ and $\psi(2S)$
  - **Non Prompt**
    - from $b$-hadron decays
- Very low $p_T$ range covered using first 314 nb$^{-1}$ of data
- Statistical errors from 2 to 9%
- Systematical uncertainties of few% (except polarization)

Unpolarized scenario results

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Non prompt Fraction

- Fraction coming from b-decay extracted with a 2-Dimensional fit of invariant mass and "pseudo-proper" decay length

\[ l_{J/\psi} = \frac{L_{xy} \cdot m_{J/\psi}}{p_T} \]

- \( l_{J/\psi} \) distribution components:
  - prompt \( \rightarrow \) Resolution function
  - non prompt \( \rightarrow \) Resolution function convoluted with exponential
  - background \( \rightarrow \) Pre-fitted in mass sidebands

- Decay length resolution described by "per-event uncertainty" on \( l_{J/\psi} \)
- Results in agreement with CDF and ATLAS

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- Excellent agreement with NRQCD predictions
  - For prompt $J/\psi$, feed down effect included in theory
  - remarkable for $\psi(2S)$ in absence of feed-down
- Typical uncertainties $\sim 5\%$ on $J/\psi$ [$\psi(2S)$] cross-sections
- Polarization uncertainty studied in 4 “extreme” scenarios, effects up to $20[30]\%$ for $J/\psi$ [$\psi(2S)$]

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B → ψ(nS)X cross sections

- Comparison with FONLL predictions:
  - For J/ψ:
    - agreement below 30 GeV
    - above 30 GeV FONLL overestimate data
  - For ψ(2S):
    - Shape agreement in the measurement range
    - Uniform scale discrepancy found
    - improved determination of BR
\( \psi(2S) \) to \( J/\psi \) cross-sections ratios

- **Cross Section Ratio calculation:**
  - Systematic uncertainties largely cancel (Luminosity, Single Muon Efficiencies...)
  - Direct production with same polarization
    - Residual polarization effect from \( J/\psi \) coming from feed-down
  - No \(|y|\) dependence seen, results as function of \( p_T \)

- **\( B \rightarrow \psi(2S) X \) Branching Fraction**
  - measured fitting the non-prompt cross-section ratio with FONLL or EvtGen curves
  \[
  B(B \rightarrow \psi(2S)X) = (3.08 \pm 0.12(\text{stat.}+\text{syst.}) \pm 0.13(\text{theor.}) \pm 0.42(B_{PDG})) \cdot 10^{-3}
  \]
  - In agreement with world average \((4.8\pm2.4)\cdot10^{-3}\)
    - improving relative uncertainty by factor 3
    - main uncertainties from other PDG BRs
\( \Upsilon(nS) \) Cross Sections

\[
\sigma(pp \to \Upsilon(1S)X) \cdot B(\Upsilon(1S) \to \mu^+\mu^-) = 7.37 \pm 0.13^{\text{(stat.)}}_{\pm 0.42}^{+0.61}_{-0.42} (\text{syst.}) \pm 0.81 (\text{lumi.}) \text{ nb}
\]
\[
\sigma(pp \to \Upsilon(2S)X) \cdot B(\Upsilon(2S) \to \mu^+\mu^-) = 1.90 \pm 0.09^{\text{(stat.)}}_{\pm 0.14}^{+0.20}_{-0.14} (\text{syst.}) \pm 0.24 (\text{lumi.}) \text{ nb}
\]
\[
\sigma(pp \to \Upsilon(3S)X) \cdot B(\Upsilon(3S) \to \mu^+\mu^-) = 1.02 \pm 0.07^{\text{(stat.)}}_{\pm 0.08}^{+0.11}_{-0.08} (\text{syst.}) \pm 0.11 (\text{lumi.}) \text{ nb}
\]

- \( \Upsilon(1S) \) and \( \Upsilon(2S) \) include feed-down from higher-mass states
- Unpolarized \( \Upsilon(nS) \) assumption
  - Extreme polarization change cross sections by about 20%

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**\( \Upsilon(1S) \) Cross Section**

Consistent shape to PYTHIA
- PYTHIA overestimates the integrated cross section by a factor 2

Results compared to D0 and CDF measurements
- Assuming cross section uniform in rapidity an increase by a factor 3 is observed at \( \sqrt{s} = 7 \) TeV

Differential cross-section vs rapidity:
- slight decrease towards \(|y| = 2\) consistent with PYTHIA
\( \chi_{cJ} \rightarrow J/\psi \gamma \) mass distribution

- Excellent resolution (< 10 MeV) for photons converted in the tracker volume
- \( \chi_{c1} \) and \( \chi_{c2} \) (\( \Delta m \sim 45 \) MeV) peaks resolved in the \( J/\psi \gamma \) spectrum
- Signal modeled by 3 Crystal Ball functions with common parameters
- Studies on \( \chi_{cJ} \) states
  - discriminate between different theoretical production models
  - evaluate the feed-down corrections to prompt \( J/\psi \) production

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The X(3872) state

- Discovered in 2003 by Belle → its nature still unclear
- A clear signal is established in 2010 in the $J/\psi \, \pi^+ \, \pi^-$ decay channel

Starting from reconstructed $J/\psi$
- Searched pair of compatible good quality opposite-charged tracks in $\Delta R(\pi, J/\psi) < 0.7$
- Performed 4-track vertex fit with $J/\psi$ mass fixed to the PDG value
- Kept good quality candidates in the kinematic region
  $p_T(X) > 8$ GeV and $|y(X)| < 2.2$

Unbinned maximum likelihood fit
- $m_{\psi(2S)} = 3685.9 \pm 0.1$ (stat. only) MeV
- $m_{X(3872)} = 3870.2 \pm 1.9$ (stat. only) MeV
- $\sigma_{1\psi(2S)} = 8.1 \pm 0.6$ MeV
- $\sigma_{2\psi(2S)} = 3.3 \pm 0.3$ MeV
- $\sigma_{X(3872)} = 6.3 \pm 1.3$ MeV

PDG values
- $m_{\psi(2S)} = 3686.09 \pm 0.04$ MeV
- $m_{X(3872)} = 3871.57 \pm 0.25$ MeV

CMS Preliminary

$\sqrt{s} = 7$ TeV

$\int L \, dt = 40$ pb$^{-1}$
X(3872) to $\psi(2S)$ inclusive cross section ratio

$$R = \frac{\sigma(pp \rightarrow X(3872) + \text{anything}) \cdot \text{BR}(X(3872) \rightarrow J/\psi \pi^+\pi^-)}{\sigma(pp \rightarrow \psi' + \text{anything}) \cdot \text{BR}(\psi' \rightarrow J/\psi \pi^+\pi^-)}$$

- Acceptance and efficiency correction from simulation are applied on the yields extracted from the mass spectrum
  - Pythia 6 with mass of $\chi_{c1}$ ($J^{PC}=1^{++}$) set to 3.872 GeV
  - Null polarization assumed
  - 30% non-prompt fraction assumed
- Ratio results

$$R = 0.087 \pm 0.017 \text{ (stat.)} \pm 0.009 \text{ (syst.)}$$

- In 2011 larger statistic collected with a $J/\psi$ trigger restricted to the CMS barrel
- With first 896 pb$^{-1}$
  - $N_{\psi(2S)} = 72594 \pm 518 \text{ (stat)}$
  - $N_{X(3872)} = 5303 \pm 341 \text{ (stat)}$
Conclusions

CMS has issued several studies on heavy quarkonia with the first LHC data:

- Measurement of $J/\psi$ cross section from 0 to 70 GeV/c with large rapidity coverage ($|y|<2.4$)

- Differential cross-sections in $p_T$ and $|y|$ of $J/\psi$ and $\psi(2S)$ mesons
  - prompt and non-prompt contributions separated
  - compatible results to NRQCD prediction up to 30 GeV/c for prompt production
  - uniform scale discrepancy found and explained for non-prompt $\psi(2S)$ production w.r.t. FONLL
  - consistent results with other LHC experiments
  - improved relative uncertainty for BR(B->$\psi(2S)\ X$) of a factor 3

- Differential cross-sections in $p_T$ for $\Upsilon(nS)$ states
  - shape compatible to PYTHIA and results at Tevatron

- First measurement for the $X(3872)$ to $\psi(2S)$ cross section ratio

- $\chi_{cJ}$ peaks resolved in their radiative decay to $J/\psi$, using converted photons
BACKUP
The CMS detector

**Solenoid**
- 3.8 T B-field

**Tracker**

**Muon Barrel**
- Silicon Strips
- Pixels
- Drift Tubes (DT)
- Resistive Plate Chambers (RPC)

**Calorimeters**
- ECAL
  - Scintillating PbWO$_4$
  - Crystals
- HCAL
  - Plastic scintillator/brass sandwich

**Muon Endcaps**
- Resistive Plate Chambers (RPC)
- Cathode Strip Chambers (CSC)
Acceptances

Single Muon Acceptance

\[ p_T^\mu \text{(GeV/c)} \]

\[ \eta^\mu \]

\[ p_T^\psi \text{(GeV/c)} \]

\[ |y| \]

\[ \psi \text{ Acceptance} \]

\[ \Upsilon(nS) \text{ Acceptance} \]

\[ A^\Upsilon \]

\[ p_T^\Upsilon \text{(GeV/c)} \]

Polarized \[ \Upsilon(nS) \text{ Acceptance} \]

\[ A^\Upsilon(|y|<2) \]

\[ p_T^\psi \text{(GeV/c)} \]

\[ |y|^{|y|<2} \]

\[ \begin{align*}
\text{Unpol} & \\
\text{HX T} & \\
\text{HX L} & \\
\text{CS T} & \\
\text{CS L} & 
\end{align*} \]
First CMS paper on $J/\psi$

\[ \sigma(pp \rightarrow J/\psi + X) \cdot \text{BR}(J/\psi \rightarrow \mu^+\mu^-) = 70.9 \pm 2.1 \text{(stat)} \pm 3.0 \text{(syst)} \pm 7.8 \text{(luminosity)} \text{ nb} \]

\[ \sigma(pp \rightarrow bX \rightarrow J/\psi X) \cdot \text{BR}(J/\psi \rightarrow \mu^+\mu^-) = 26.0 \pm 1.4 \text{ (stat)} \pm 1.6 \text{ (syst)} \pm 2.9 \text{ (luminosity)} \text{ nb} \]
$$\psi(nS) \text{ Cross-section overview}$$

$$\frac{d^2\sigma}{dp_T dy}(J/\psi) \cdot B(J/\psi \to \mu^+ \mu^-) = \frac{N_{J/\psi}^{corr}(p_T, |y|)}{\int L dt \cdot \Delta p_T \cdot \Delta y}$$

- $N_{\text{fit}} = \text{signal yield from fit to } \mu\mu \text{ invariant mass}$
- $\int L dt = \text{integrated luminosity (4% uncertainty)}$
- $A = \text{geometrical and kinematical acceptance}$
  - Strongly dependent on production polarization
- $\epsilon = \text{dimuon efficiency} = \epsilon(\mu^+) \epsilon(\mu^-) \rho \epsilon_{\text{vertex}}$
  - single muon trigger and reconstruction $\epsilon(\mu)$, data-driven via Tag & Probe
  - vertexing of opposite sign dimuons (Prob>1%)
  - selection based on high quality tracks associated to muon segments:
    - cuts on $n_{\text{hits}}, \chi^2, |d_{xy}|, |d_z|$
  - $\rho$ express the correlation between the two $\mu$ efficiencies
    - trigger settings remove too close $\mu$ (to reduce single $\mu$ faking double $\mu$), inducing sizable correlations $\Rightarrow$ Offline rejection of forward muons bending towards each other
$\psi(nS)$ Cross Sections

uncorrected for acceptance

![Graph of $J/\psi$ cross sections](image)

![Graph of $\psi(2S)$ cross sections](image)

**Prompt $J/\psi$**

- $\mu^+\mu^-$, uncorrected for acceptance
- $p_T$ range: 6 to 50 GeV/c

**Non-Prompt $J/\psi$**

- $\mu^+\mu^-$, uncorrected for acceptance
- $p_T$ range: 6 to 50 GeV/c

**Prompt $\psi(2S)$**

- $\mu^+\mu^-$, uncorrected for acceptance
- $p_T$ range: 6 to 30 GeV/c

**Non-Prompt $\psi(2S)$**

- $\mu^+\mu^-$, uncorrected for acceptance
- $p_T$ range: 6 to 30 GeV/c
\(\psi(nS)\) Integrated Cross Sections

**J/\psi**

- \(8.0 < p_T < 70.0 \ \text{GeV/c}\) for \(|y| < 0.9\)
- \(8.0 < p_T < 45.0 \ \text{GeV/c}\) for \(0.9 < |y| < 1.2\)
- \(6.5 < p_T < 45.0 \ \text{GeV/c}\) for \(1.2 < |y| < 1.6\)
- \(6.5 < p_T < 30.0 \ \text{GeV/c}\) for \(1.6 < |y| < 2.1\)
- \(5.5 < p_T < 30.0 \ \text{GeV/c}\) for \(2.1 < |y| < 2.4\)

**\(\psi(2S)\)**

- \(6.5 < p_T < 30.0 \ \text{GeV/c}\) for \(|y| < 1.2\)
- \(5.5 < p_T < 30.0 \ \text{GeV/c}\) for \(1.2 < |y| < 2.4\)

Corrected for acceptance:

\[B(J/\psi \rightarrow \mu^+\mu^-) \cdot \sigma(pp \rightarrow \text{prompt } J/\psi) = 54.5 \pm 0.3 \pm 2.3 \pm 2.2 \ \text{nb}\]

\[B(J/\psi \rightarrow \mu^+\mu^-) \cdot \sigma(pp \rightarrow bX \rightarrow J/\psi X) = 20.2 \pm 0.2 \pm 0.8 \pm 0.8 \ \text{nb}\]

\[B(\psi(2S) \rightarrow \mu^+\mu^-) \cdot \sigma(pp \rightarrow \text{prompt } \psi(2S)) = 3.53 \pm 0.26 \pm 0.32 \pm 0.14 \ \text{nb}\]

\[B(\psi(2S) \rightarrow \mu^+\mu^-) \cdot \sigma(pp \rightarrow bX \rightarrow \psi(2S)X) = 1.47 \pm 0.12 \pm 0.13 \pm 0.06 \ \text{nb}\]

Uncorrected for acceptance:

\[B(J/\psi \rightarrow \mu^+\mu^-) \cdot \sigma(pp \rightarrow \text{prompt } J/\psi) = 9.83 \pm 0.03 \pm 0.38 \pm 0.39 \ \text{nb}\]

\[B(J/\psi \rightarrow \mu^+\mu^-) \cdot \sigma(pp \rightarrow bX \rightarrow J/\psi X) = 4.67 \pm 0.02 \pm 0.17 \pm 0.19 \ \text{nb}\]

\[B(\psi(2S) \rightarrow \mu^+\mu^-) \cdot \sigma(pp \rightarrow \text{prompt } \psi(2S)) = 0.410 \pm 0.009 \pm 0.023 \pm 0.016 \ \text{nb}\]

\[B(\psi(2S) \rightarrow \mu^+\mu^-) \cdot \sigma(pp \rightarrow bX \rightarrow \psi(2S)X) = 0.235 \pm 0.006 \pm 0.013 \pm 0.009 \ \text{nb}\]
Above $p_T \approx 20$ GeV, more than 50% of the $J/\psi$ and $\psi(2S)$ mesons result from $B$ decays.