Quarkonium Physics at CMS

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on Behalf of the CMS Collaboration
CMS Quarkonium Studies

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

- 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 already studied many quarkonia with di-muons final states
  - production cross section for S-wave quarkonia
  - observation of $\chi_{cJ}$ states
  - study of the X(3872) exotic
Muons in CMS

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

- Inner Tracker:
  - Silicon pixel and strip layers

- Muon System
  - 3 types of gaseous detectors

- Trigger choices of key importance for low energy studies
  - Physical objects reconstructed at trigger level to select high purity signals

High precision $p_T$ measurement

Trigger & Identification

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2010 Run

CMS

$\sqrt{s} = 7$ TeV

$L_{int} = 40$ pb$^{-1}$

2011 Run Strategy

2011 Run, L = 1.1 fb$^{-1}$

CMS $\sqrt{s} = 7$ TeV

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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
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

- With 37 pb$^{-1}$ already covered a $p_T$ range up to 70 GeV/c

\[
\frac{d^2\sigma}{dp_T dy} (J/\psi) \cdot B(J/\psi \rightarrow \mu^+\mu^-) = \frac{N_{J/\psi}^{\text{corr}} (p_T, |y|)}{\int L \, dt \cdot \Delta p_T \cdot \Delta y}
\]
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 ATLAS, higher fraction of \( J/\psi \) from B-decays at LHC energy w.r.t. CDF

Results from b hadrons:

\[ \text{Fraction of } J/\psi \text{ from } b \text{ hadrons} \]

- ATLAS: 2.3 pb
- CMS: 36.7 pb
- CDF: \( \sqrt{s} = 1.96 \text{ TeV} \) \( |y| < 0.75 \)
- \( \sqrt{s} = 7 \text{ TeV} \) \( 0.00 < |y| < 0.9 \)

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**ψ(nS) cross sections**

Excellent agreement with NRQCD predictions:
- for J/ψ, feed down effect included in theory
- reduced theoretical uncertainties for ψ (2S) in absence of feed-down

Comparison with FONLL predictions:
- For J/ψ:
  - agreement below 30 GeV
  - above 30 GeV FONLL overestimate data
- For ψ (2S):
  - agreement in the measurement region
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

$$B(B \rightarrow \psi(2S)X) = (3.08 \pm 0.12\text{(stat.+syst.)} \pm 0.13\text{(theor.)} \pm 0.42(B_{PDG})) \cdot 10^{-3}$$
- In agreement with world average $(4.8\pm2.4)\cdot10^{-3}$
  - improving relative uncertainty by factor 3
  - main uncertainties from other PDG BRs
**Unpolarized \(\Upsilon(nS)\) assumption**

- \(\Upsilon(1S)\) and \(\Upsilon(2S)\) include **feed-down** from higher-mass states

- 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

- **Consistent shape to PYTHIA both as function of** \(p_T\) **and** \(|y|\)
  - integrated cross section overestimated by a factor 2

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$\chi_{cJ} \rightarrow J/\psi \gamma$ mass distribution

- **Excellent resolution** (< 10 MeV) for photons converted in the tracker volume

- $\chi_{c1}$ and $\chi_{c2}$ ($\Delta m \approx 45$ MeV) peaks resolved in the $J/\psi \gamma$ spectrum

- **Studies on $\chi_{cJ}$ states**
  - discriminate between different theoretical production models
  - evaluate the feed-down corrections to prompt $J/\psi$ production
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
- A pair of compatible good quality opposite-charged tracks associated to a reconstructed $J/\psi$
  - 4-track vertex fit with $J/\psi$ mass fixed to the PDG value
- Measured the quantity
  \[ R = \frac{\sigma(pp \to X(3872) + \text{anything})BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything})BR(\psi(2S) \to J/\psi\pi^+\pi^-)} \]
  in the kinematical region
  \[ p_T(X) > 8 \text{ GeV and } |y(X)| < 2.2 \]
- Acceptance and efficiency correction from simulation applied on the mass spectrum yields
  - 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
  \[ R = 0.087 \pm 0.017 \text{ (stat.)} \pm 0.009 \text{ (syst.)} \]
Conclusions

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

- **Differential cross-sections** in $p_T$ and $|y|$ of $J/\psi$ and $\psi(2S)$ mesons
  - prompt and non-prompt contributions separated
  - general good compatibility with NRQCD and FONLL predictions
  - consistent results with other LHC experiments

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

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

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

“J/ψ and ψ(2S) production in pp collisions at √s = 7 TeV”, JHEP 02, 011 (2012)


“Observation of the χc states with 1.1fb⁻¹”, CERN-CMS-DP-2011-011

“Measurement of the production cross section ratio of X(3872) and ψ(2S)”, CMS-PAS-BPH-10-018
BACKUP
The CMS detector

SOLENOID
3.8 T B-field

TRACKER

MCAL
Scintillating PbWO$_4$
Crystals

ECAL
Silicon Strips
Pixels

CALORIMETERS
HCAL
Plastic scintillator/brass sandwich

Resistive Plate Chambers (RPC)

MUON BARREL

Drift Tubes (DT)

Resistive Plate Chambers (RPC)

Cathode Strip Chambers (CSC)

Resistive Plate Chambers (RPC)

MUON END CAPS

wires

straps

3.8 T B-field

Tracker

Endcaps

Silicon Strips
Pixels

Resistive Plate Chambers (RPC)

Cathode Strip Chambers (CSC)

Resistive Plate Chambers (RPC)
X(3872) with 2011 Data

- In 2011 larger statistic collected with a $J/\psi$ trigger restricted to the CMS barrel

- With first 896 pb$^{-1}$
  - $N_{\psi(2S)} = 72594 \pm 518 \text{ (stat)}$
  - $N_{X(3872)} = 5303 \pm 341 \text{ (stat)}$
Acceptances

- Single Muon Acceptance
- $\Upsilon(nS)$ Acceptance
- Polarized $\Upsilon(nS)$ Acceptance

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First CMS paper on J/ψ

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

\[ \sigma(pp \rightarrow bX \rightarrow J/\psi X) \cdot \text{BR}(J/\psi \rightarrow \mu^+\mu^-) = 26.0 \pm 1.4\text{ (stat)} \pm 1.6\text{ (syst)} \pm 2.9\text{ (luminosity)} \text{ nb} \]
\[ \frac{d^2 \sigma}{dp_T dy} (J/\psi) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = \frac{N_{corr}^{J/\psi}(p_T, |y|)}{\int L dt \cdot \Delta p_T \cdot \Delta y} \]

\( N_{\text{fit}} = \) signal yield from fit to \( \mu\mu \) invariant mass

\( \int L dt = \) integrated luminosity (4% uncertainty)

\( A = \) geometrical and kinematical acceptance

\[ \begin{align*}
\text{Strongly dependent on production polarization} & \\
|\eta^\mu| < 1.2 & \rightarrow p_T > 4 \text{ GeV/c} \\
1.2 < |\eta^\mu| < 2.4 & \rightarrow p_T > 3.3 \text{ GeV/c}
\end{align*} \]

\( \mathcal{E} = \) dimuon efficiency = \( \mathcal{E}(\mu^+) \mathcal{E}(\mu^-) \rho \mathcal{E}_{\text{vertex}} \)

- single muon trigger and reconstruction \( \mathcal{E}(\mu) \), 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

\( \text{o trigger settings remove too close } \mu \text{ (to reduce single } \mu \text{ faking double } \mu \text{), inducing sizable correlations} \rightarrow \text{Offline rejection of forward muons bending towards each other} \)
\( \psi(nS) \) Cross Sections

uncorrected for acceptance

 prompt \( J/\psi \rightarrow \mu^+ \mu^- \), uncorrected for acceptance

\[
\frac{d^2 \sigma_{J/\psi}}{dp_T dy} (\text{nb}/(\text{GeV}/c))
\]

prompt \( \psi(2S) \rightarrow \mu^+ \mu^- \), uncorrected for acceptance

\[
\frac{d^2 \sigma_{\psi(2S)}}{dp_T dy} (\text{nb}/(\text{GeV}/c))
\]

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Above $p_T \approx 20$ GeV, more than 50% of the $J/\psi$ and $\psi(2S)$ mesons result from $B$ decays.