

Quarkonium Production with the CMS Experiment

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Results from studies of quarkonium production are presented from the CMS experiment at the LHC in proton-proton collisions at $\sqrt{s} = 7$ TeV. We report measurements of the ratio of χ_{c2}/χ_{c1} production versus p_T and $\Upsilon(nS)$ production vs rapidity and p_T for the 1S, 2S and 3S states. Reconstruction of B_c mesons is also presented in two decay channels.

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1. Introduction

The CMS experiment at the LHC pursues a diverse program of heavy quarkonia measurements. We present here some recent highlights of this program, including measurements of the χ_{c2}/χ_{c1} production ratio as a function of p_T and the production of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ as functions of rapidity and p_T , including the ratios of the Υ states. We also present the observation of the B_c meson in two decay channels. All measurements were performed with the CMS experiment using pp collision data collected at a center-of-mass energy of 7 TeV.

CMS is a general purpose experiment at the Large Hadron Collider [1]. The inner detector contains a silicon tracker composed of pixel layers at radii less than 15 cm and strip layers out to a radius of 110 cm. The central region has 3 layers of pixels and 10 layers of strips. The cylindrical geometry of the central region changes to disks in the rz plane for the forward region. Each side of the interaction region contains two endcap pixel layers and up to 12 layers of strips. The tracker, PbWO_4 electromagnetic calorimeter, and brass-scintillator hadron calorimeter are all immersed in a 3.8 T axial magnetic field. Muons are measured with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Muons, electrons and hadrons are tracked within the pseudorapidity region $|\eta| < 2.4$ with p_T resolution of about 1.5% for tracks used in the analyses presented here.

2. χ_c production

The relative prompt production rate of χ_{c2} and χ_{c1} is measured with 4.6 fb^{-1} of data collected at LHC at $\sqrt{s} = 7 \text{ TeV}$ [2]. The two states are reconstructed via the radiative decays $\chi_c \rightarrow J/\psi + \gamma$, with the photon reconstructed through conversions into e^+e^- pairs in the tracking detector. The measurements are reported for the kinematic acceptance defined by $|y(J/\psi)| < 1.0$ and $p_T(\gamma) > 0.5 \text{ GeV}$. Due to the small mass difference between the χ_{c1} and χ_{c2} with the J/ψ , the photons from the radiative decays are generally at low momentum, with most between 0.5 and 6.0 GeV in the laboratory frame. Reconstruction of such low momentum photons with precise energy resolution is only possible through the precise reconstruction of electron tracks from photon conversions.

Oppositely charged muon candidates are fit to a common vertex to produce J/ψ candidates, where the two muons are also used to trigger the event. To select prompt production only, the proper decay length of the J/ψ candidate is required to be less than $30 \mu\text{m}$, which reduces non-prompt contamination to less than 1%. Converted photons are selected by fitting two oppositely charged electron candidates to a common vertex and selecting those that are consistent with zero mass and parallel tracks at the point of conversion. The conversion candidate is required to be consistent with a reconstructed primary vertex in the event. Only the tracker is used in the reconstruction of the electron candidates, with no information from the calorimeters. Conversion candidates which, when paired with another photon candidate in the event, are consistent with the π^0 mass are rejected. Conversion candidates are then combined with J/ψ candidates to form χ_c candidates. To avoid large uncertainty in the dimuon mass, the mass difference between the dimuon plus photon system and the dimuon alone is considered when calculating event yields. Figure 1 shows the mass distribution for selected χ_c candidates.

To measure the ratio of χ_{c2}/χ_{c1} production, the ratio of efficiencies is required. Many uncertainties cancel in the use of the ratio of efficiencies. MC simulation is used to determine the ratio of the acceptance and reconstruction efficiency for the two states, where a maximum difference of 10% is observed. The yields and efficiency ratios are determined in slices of J/ψ p_T to measure the differential production ratio. The results are shown in Fig. 1 with the assumption of unpolarized production of both χ_{c1} and χ_{c2} . Because the production polarization of these χ_c states is unknown, the effects of different polarization assumptions are reported in [2] and are found to be as large as $\sim 30\%$ on the ratio. Figure 2 shows the results compared to the predictions from several theoretical models. In order to match the assumptions and phase space used for the theoretical calculations, the results are reported in several configurations. No single model is able to completely describe the reported results.

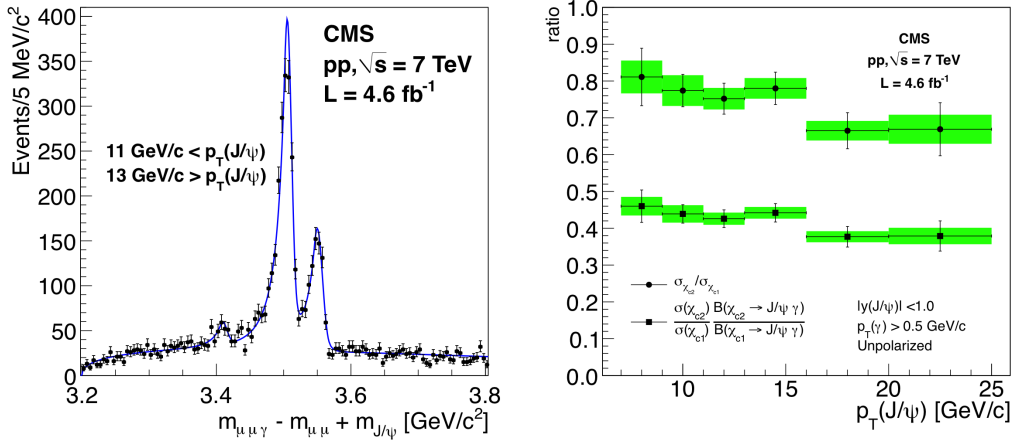


Figure 1: Invariant mass distribution for χ_c candidates with $11 < p_T(J/\psi) < 13$ GeV (left) and χ_{c2}/χ_{c1} production results versus $p_T(J/\psi)$ (right).

3. $\Upsilon(nS)$ production

The Υ production cross section is measured using $35.8 \pm 1.4 \text{ pb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV, collected with the CMS detector at the CERN LHC in 2010 [3]. The Υ candidates are reconstructed from oppositely charged muon pairs, where the two muons are also used to trigger the event. A mass resolution of 50 ± 2 MeV is obtained for central muons with $|\eta^\mu| < 1.0$, while the resolution is worse for forward candidates. Figure 3 shows the dimuon invariant mass distribution in the region of the Υ resonances. The efficiency to reconstruct an Υ decay is divided into terms for the detector acceptance determined from MC simulation and the triggering and reconstruction efficiencies determined from J/ψ events in data. For the differential cross section measurement, the efficiencies are determined in bins of Υ rapidity and p_T .

Candidate events are weighted by the inverse of the efficiency. The weighted distributions are fit in bins of Υ rapidity and p_T to determine the efficiency-corrected yields, which are divided by the luminosity to obtain the differential cross sections vs rapidity and p_T . Figure 3 shows the

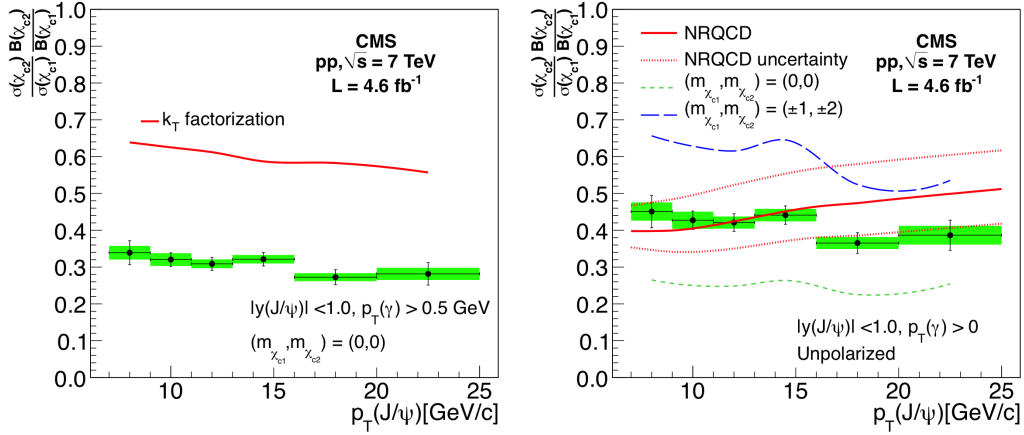


Figure 2: Production results for χ_{c2}/χ_{c1} versus $p_T(J/\psi)$ compared to various theoretical predictions.

differential cross section ratios between the $\Upsilon(nS)$ states, while Fig. 4 shows the differential cross sections versus p_T and rapidity for the individual states.

The total observed yield of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ reconstructed in the dimuon decay channel are 77931 ± 431 , 23847 ± 290 , and 12308 ± 258 , respectively. Integrated over the range $p_T < 50$ GeV and $|y| < 2.4$, assuming unpolarized $\Upsilon(nS)$ production, we find the product of the $\Upsilon(nS)$ production cross section and branching fraction to be

$$\sigma(pp \rightarrow \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+ \mu^-) = (8.56 \pm 0.05_{-0.56}^{+0.69} \pm 0.34) \text{ nb},$$

$$\sigma(pp \rightarrow \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \rightarrow \mu^+ \mu^-) = (2.23 \pm 0.03_{-0.16}^{+0.19} \pm 0.09) \text{ nb},$$

$$\sigma(pp \rightarrow \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.02_{-0.10}^{+0.11} \pm 0.05) \text{ nb}.$$

where the first uncertainty is statistical, the second is systematic and the third is associated with the estimation of the integrated luminosity of the data sample. The shapes of the differential cross section measurements versus p_T and $|y|$ are found to be in good agreement with the predictions from PYTHIA MC simulation.

4. Observation of B_c

The B_c^+ meson, consisting of one beauty quark and one charm quark, presents a unique laboratory to study heavy quark dynamics. We present the observation of two decay channels at CMS, $B_c^+ \rightarrow J/\psi \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ [4]. In both channels, J/ψ decays to two muons are used to trigger events. Either one or three charged pion candidates are combined with the J/ψ candidate to form B_c^+ candidates. A total yield of 330 ± 36 events are observed for the one pion decay channel, while 108 ± 19 events are observed for the three pion decay channel. Figure 5 shows the invariant mass distribution for both decay channels.

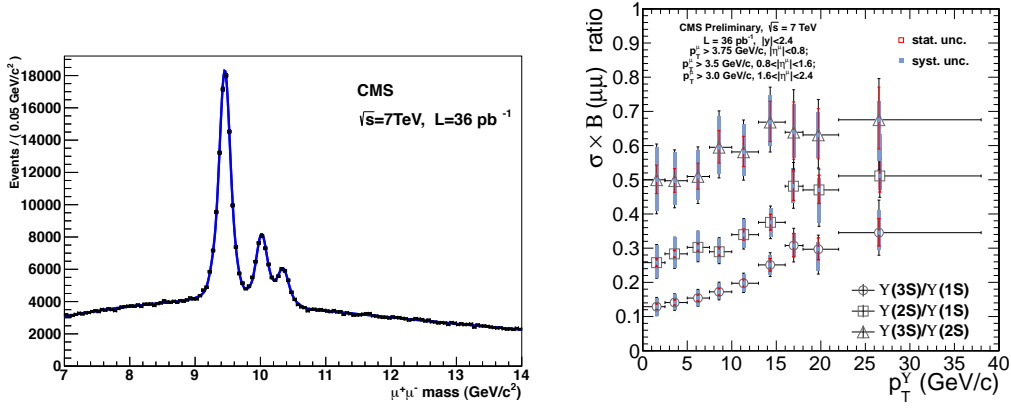


Figure 3: Dimuon invariant mass distribution with fitted peaks for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states (left) and the Υ production ratios versus p_T (right).

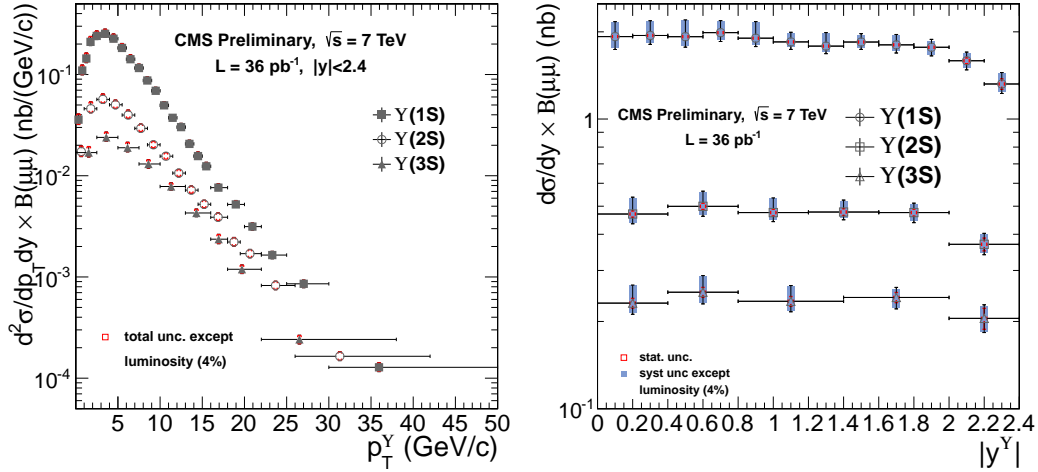


Figure 4: Differential production cross section for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ as a function of p_T (left) and rapidity (right).

5. Conclusion

A selection of results from the CMS heavy quarkonia physics program is shown, including differential measurements of the χ_{c2}/χ_{c1} production ratio and the production of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. The observation of the B_c meson is also shown. These measurements of heavy quark production further our understanding of fundamental quantum chromodynamics, which still does not offer a complete theoretical picture of the results presented here.

References

- [1] The CMS Collaboration, *JINST* **3**, S08004 (2008).
- [2] S. Chatrchyan *et al.* [CMS Collaboration], Submitted to: *Eur.Phys.Jour.* [arXiv:1210.0875 [hep-ex]].

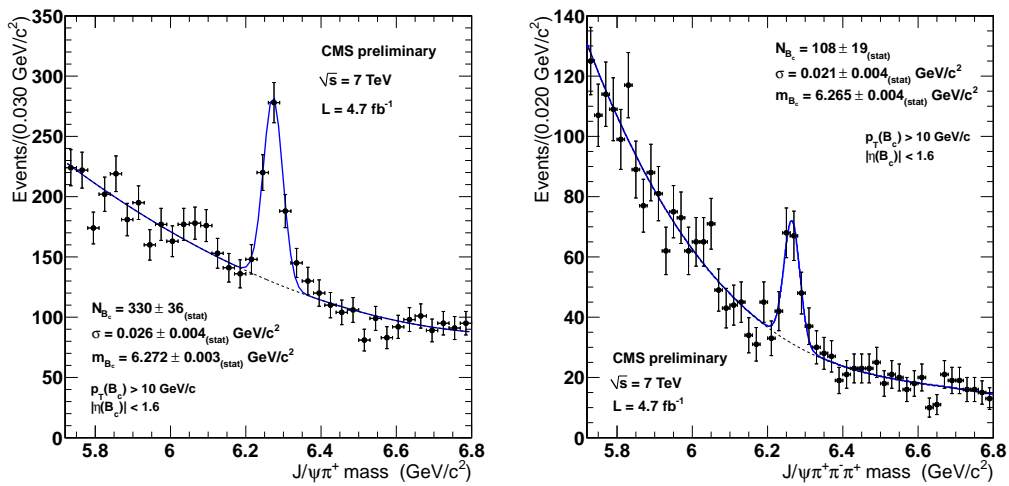


Figure 5: Invariant mass distributions for B_c candidates in the $J/\psi\pi^+$ channel (left) and $J/\psi\pi^+\pi^-\pi^+$ channel (right).

- [3] The CMS Collaboration, CMS Physics Analysis Summary **BPH-11-001**, <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11001>, (2012).
- [4] The CMS Collaboration, CMS Physics Analysis Summary **BPH-11-003**, <http://cds.cern.ch/record/1461944>, (2012).