The Compact Muon Solenoid Experiment

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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Quarkonium cross sections and polarizations in pp collisions with CMS

Charles Ferraioli for the CMS Collaboration

Abstract

According to NRQCD, quarkonium production starts with the (short-distance) production of a pre-resonant quark-antiquark pair, $Q\bar{Q}$, that then binds into the observed quarkonium state, changing (octet) or not (singlet) its angular momentum and spin, with probabilities (long-distance matrix elements, LDMEs) conjectured to be constant and universal identical LDMEs should be extracted from, e.g., proton-(anti)proton and $e+e-$ data. The non-perturbative bound state formation described by the octet LDMEs involves the interaction with the surrounding medium in the event, since the initial $Q\bar{Q}$ must neutralize its colour by absorbing or emitting soft gluons the LDMEs could be different between proton-proton and nucleus-nucleus collisions. Such a difference, besides calling to question the universality hypothesis of NRQCD, would play a crucial role in the interpretation of the quarkonium suppression patterns as signatures of quark-gluon plasma formation. Unlike the measurements of quarkonium differential cross sections, which reflect partonic processes and are sensitive to initial-state effects (modified parton distribution functions, Cronin effect, parton energy loss, etc.), the polarization measurements are unambiguous probes of the (final state) quarkonium formation process, determined by the quantum properties of the $Q\bar{Q}$ a change in polarization would be a direct signal, virtually unaffected by initial-state phenomena, of a change in the binding mechanism. This talk presents the charmonium and bottomonium cross sections and polarizations measured by CMS, using dimuon samples collected in pp collisions at 7 TeV. The cross sections of five S-wave states extend up to or exceed $p_T = 100$ GeV, probing kinematical windows where the theory calculations are supposed to be the most reliable. The Upsilon cross sections and polarizations are also shown (for the first time) as a function of the number of charged particles produced in the collision. These results provide crucial inputs to a better understanding of quarkonium production as a signal of new physics in PbPb collisions.

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Quarkonium cross sections and polarizations in pp collisions with CMS

C. Christopher Ferraioli

Abstract

According to NRQCD, quarkonium production starts with the production of a pre-resonant quark-antiquark ($Q\bar{Q}$) pair that then binds into the observed quarkonium state through a possible interaction with surroundings. Understanding this interaction would play a crucial role in the interpretation of the quarkonium suppression patterns as signatures of quark-gluon plasma formation. Unlike the measurements of quarkonium differential cross sections, which reflect partonic processes and are sensitive to initial-state effects, the polarization measurements are unambiguous probes of the final-state quarkonium formation process, determined by the quantum properties of the $Q\bar{Q}$: a change in polarization would be a direct signal, virtually unaffected by initial-state phenomena, of a change in binding mechanism. This report presents the $\psi(nS)$ and $\Upsilon(nS)$ cross sections and polarizations measured by CMS, using dimuon samples collected in pp collisions at $\sqrt{s} = 7$ TeV. The cross sections of five S-wave states extend up to or exceed $p_T = 100$ GeV, probing kinematical windows where the theory calculations are supposed to be the most reliable. The polarizations are measured up to high p_T at midrapidity, and the Upsilon polarizations are also shown as a function of the number of charged particles produced in the pp collision.

Keywords:

1. Introduction

Quarkonium suppression is a predicted signal of the presence of a quark-gluon plasma (QGP) [1]. CMS has observed the sequential suppression of $\Upsilon(nS)$ particles in $\sqrt{s_{NN}} = 2.76$ TeV PbPb collisions in which the most tightly bound $\Upsilon(1S)$ was found to be less suppressed than the higher order $\Upsilon(2S)$ and $\Upsilon(3S)$ states [2]. This measurement is clouded by additional effects occurring either before or after the $\Upsilon(nS)$ production. Initial-state effects, which alter production prior to the collision, include parton energy loss and nuclear modifications of the parton distribution functions. Final-state effects unrelated to the QGP, such as nuclear absorption processes and dissociative collisions with other particles, can also affect the suppression patterns. To understand these effects, it is necessary to study quarkonium production in pp collisions.

Non-relativistic QCD (NRQCD)[3] factorizes quarkonium production in two steps. First, a possibly colored $Q\bar{Q}$ pair is created, described by short-distance

coefficients (SDCs), which are calculated with perturbative QCD as functions of the $Q\bar{Q}$ momentum. The next step, separated in time and space, is described by long-distance matrix elements (LDMEs), which reflect the probability that the $Q\bar{Q}$ pair evolves into a bound quarkonium. All but four LDMEs may be neglected in the non-relativistic limit, $v^2 \ll 1$, so that an S-wave quarkonium state should be dominantly produced in a color-singlet, $^3S_1^{[1]}$, or one of three color-octet states, $^1S_0^{[8]}$, $^3S_1^{[8]}$, and $^3P_j^{[8]}$. If the $Q\bar{Q}$ pair is formed in a color-octet state, it must interact with its surroundings to neutralize its color.

The LDMEs are expected to be independent from the process in which the pre-resonant $Q\bar{Q}$ was initially formed, but this hypothesis needs to be experimentally verified. Studying quarkonium formation in pp collisions as a function of charged particle multiplicity, N_{ch} , and in heavy-ion collisions, provides a test of LDME universality.

Unlike what happens with the cross sections, which

are dependent on initial-state processes, the polarization is a direct measurement of the quantum properties of the $Q\bar{Q}$ pair. Changes in the measured quarkonium polarization with respect to the quarkonium's surroundings would be a direct signal of a change in the quarkonium formation mechanism.

This document reports p_T and y double-differential measurements of the $\psi(nS)$ and $\Upsilon(nS)$ cross sections and polarizations, as well as $\Upsilon(nS)$ polarizations as a function of the charged particle multiplicity (N_{ch}), in pp collisions at $\sqrt{s} = 7$ TeV. For more details of these CMS measurements, see Refs. [4, 5, 6, 7, 8]. These measurements have led to a more thorough understanding of the production process in pp collisions, and will benefit the comprehension of the suppression trends observed in heavy-ion collisions.

2. Analysis Methods and Results

The datasets for these measurements were collected with the CMS detector in 2011 and correspond to integrated luminosities $\sim 5 \text{ fb}^{-1}$. A two-level trigger system was used, with the first step performed on the hardware level, accepting events with two muons. A high-level trigger further reduced the event storage rate, requiring an opposite-sign muon pair with suitable invariant mass ranges and p_T above thresholds adapted to the LHC instantaneous luminosity.

2.1. Cross Sections

The differential cross sections were calculated by determining the quarkonium yield in several kinematic bins, through fits of mass distributions. Corrections for detector efficiency and acceptance were determined using tag-and-probe and Monte Carlo simulation methods, respectively.

The double differential $\psi(nS)$ cross section analysis was performed in four rapidity bins within $|y| < 1.2$ with p_T ranges 10–95 GeV for the J/ψ and 10–75 GeV for the $\psi(2S)$. Integrated in rapidity, the p_T ranges were extended to 120 and 100 GeV, respectively. The prompt signal yields were extracted using an extended unbinned maximum-likelihood fit to the mass-lifetime two-dimensional distribution, in each (y, p_T) bin. A crystal ball function provided a good description of the signal invariant mass, while an exponential function described the continuum background. The rapidity-integrated results are presented in Fig. 1. They provide a large extension in p_T reach over previous measurements.

The $\Upsilon(nS)$ cross sections were measured up to 100 GeV in two rapidity bins. The $\Upsilon(nS)$ yields were

Figure 1: J/ψ and $\psi(2S)$ rapidity-integrated cross sections. The CMS measurements (blue circles) are compared to those from ATLAS (red squares). The green band represents a global fit to previous $\Psi(2S)$ measurements [4].

determined by building a probability density function using the measured muon momenta and their uncertainties, and accounting for final-state radiation with a generator-level simulation. This method propagates event-by-event tracking errors to the dimuon mass variable. Figure 2 show the results, which represent a large extension in p_T reach from previous measurements.

2.2. Polarization

Quarkonium polarization is measured through the angular distribution of the dimuon decay [9]. For the S-wave states,

$$W(\cos\vartheta, \varphi|\vec{\lambda}) \propto 1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi, \quad (1)$$

where ϑ and φ are the polar and azimuthal angles of the positive muon with respect to the quantization axis z of the chosen polarization frame, and the $\vec{\lambda}$ are the polarization observables that describe the anisotropy of the decay distribution. Additionally, a frame-independent parameter can be measured, $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$. CMS measured the J/ψ , $\psi(2S)$, and $\Upsilon(nS)$ polarizations, double-differentially in rapidity and p_T . Some of these results are shown in Fig. 3, along with results from the ALICE and LHCb experiments. All measurements cluster around the unpolarized limit, with no significant dependencies on p_T , y , particle identity, or level

Figure 2: The $\Upsilon(nS)$ p_T -differential cross sections measurement with the 2011 dataset (black circles), compared to previous CMS measurements (blue bands) and a theory calculation [5].

of feed-down contribution. These results strongly indicate that quarkonium production predominantly takes place through the $^1S_0^{[8]}$ channel, the only unpolarized pre-resonant state. This color-octet state must neutralize its color by soft-gluon exchanges, implying that a change in the surrounding QCD medium could impact the quarkonium formation mechanism. CMS has investigated this possibility by measuring the polarization in subsamples of increasing charged particle multiplicities.

Figure 3: $\psi(nS)$ polarizations from various LHC experiments [10].

In the first measurement of its kind and as an initial step in a broad study of QCD medium effects on quarkonium polarization, CMS has measured $\Upsilon(nS)$ polarization in pp collisions versus charged particle multiplicity, defined as the sum of weights assigned to tracks

with $p_T > 500$ MeV, reflecting the likelihood that the track originated in the primary vertex, excluding the two muons. The λ_θ , λ_φ , and $\lambda_{\theta\varphi}$ parameters measured in the center-of-mass helicity (HX) frame are shown in Fig. 4 for the $\Upsilon(1S)$, in two p_T bins. The error bars represent the 68.3% CL intervals of the total N_{ch} -dependent uncertainties. Similar results, showing negligible polarizations with no apparent trend in N_{ch} , were also seen in the Collins-Soper and perpendicular helicity frames, and for the $\Upsilon(2S)$ and $\Upsilon(3S)$. Figure 5 shows the frame-independent $\tilde{\lambda}$ results for the three Υ states, versus N_{ch} .

Figure 4: The three frame-dependent λ parameters, in the HX reference frame, for the $\Upsilon(1S)$ [6].

3. Summary and Conclusions

CMS has greatly extended the p_T reach of quarkonium production cross sections and provided unambiguous polarization measurements, excluding strong polarizations. The results suggest a common quarko-

Figure 5: The frame-independent $\tilde{\lambda}$ parameter for the $\Upsilon(nS)$, versus charged particle multiplicity [6].

nium production, during which a pre-resonant quark-antiquark pair is produced dominantly in a colored state, which requires gluon exchanges with the surrounding QCD medium to form the color-neutral quarkonium. CMS has also measured the $\Upsilon(nS)$ polarizations versus N_{ch} , to see if the quarkonium production mechanism is visibly affected by the surrounding medium. The measurements do not show significant changes versus N_{ch} , excluding strong changes of production processes between low- and high-multiplicity pp collisions.

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