PROCEEDINGS OF SCIENCE

Quarkonium production and polarization in pp collisions with the CMS detector

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Heavy quarkonium mesons constitute an ideal laboratory to study hadron formation, through the understanding of the properties of quarkonium production and polarization in hadron collisions. The currently most favored approach to model quarkonium production is non-relativistic quantum chromodynamics (NRQCD), taking advantage of the heavy quark masses to simplify QCD calculations. The experimental situation in the pre-LHC era was not satisfactory, given the ambiguous and inconsistent measurements of quarkonium polarization. New experimental input, relying on improved analysis methodologies, is required to advance the understanding of hadron formation. The LHC is a quarkonium factory, providing ideal conditions to study quarkonia in proton-proton collisions. CMS is ideally suited to study the decays of S-wave quarkonia in two muons. Furthermore, given the high granularity silicon tracker, radiative decays of P-wave quarkonia can be reconstructed with excellent momentum resolution through the reconstruction of photon conversions to e^+e^- pairs. This allowed CMS to perform measurements of cross-section ratios involving the χ states, in both the charmonium and bottomonium families.
This document discusses results of CMS quarkonium production and polarization data analyses, in proton-proton collisions, at $\sqrt{s}$ =7 TeV and 8 TeV, emphasizing the most recent measurements, including the measurement of the polarizations of all five S-wave quarkonium vector states. Results are compared to corresponding results of other experiments, and to state-of-the-art NRQCD model calculations.

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1. Introduction

Measurements of observables of quarkonium production and polarization provide vital information for the understanding of the very basic processes leading to QCD bound state formation. Quarkonia, bound states of a heavy quark and its respective antiquark ("charmonium" $c\bar{c}$ and "bottomonium" $b\bar{b}$ states), constitute an ideal laboratory to study hadron formation, given the heavy quark masses, which allow the simplification of the QCD calculations by employing non-relativistic approximations. The currently most favored approach to model quarkonium production is non-relativistic quantum chromodynamics (NRQCD), which allows non-perturbative transitions of intermediate quark-antiquark ($Q\bar{Q}$) states in color-octet configurations to contribute to quarkonium production.

The data in the Tevatron era seriously challenged NRQCD calculations [1]. However, measurements of quarkonium polarization were found to be ambiguous [2] and partially inconsistent [1]. Therefore, new experimental input, relying on improved analysis methodologies, is required to advance the understanding of hadron formation.

The LHC is a quarkonium factory, due to the high collision energies and luminosities. The CMS experiment [3] is ideally suited to study the production of S-wave quarkonia in the dimuon decay channel, and the production of P-wave quarkonia in their radiative decays. Given the very good dimuon mass, decay length and photon energy resolution, as well as the high p_{T} reach of the measurements, CMS has the potential to significantly contribute to the quest to understand quarkonium production.

This document presents an overview of the measurements of quarkonium production cross sections (Sect. 2) and quarkonium polarizations (Sect. 3) in proton-proton collisions with the CMS detector, comparing the results to those from other relevant experiments. Furthermore, comparisons to NRQCD calculations are shown in Sect. 4.

2. Quarkonium production cross section measurements

The CMS Collaboration has conducted several measurements of cross sections of the charmonium [4, 5, 6] and bottomonium [7, 8] S-wave states at $\sqrt{s}$ =7 TeV, double-differentially in p_{T} and rapidity, extending the p_{T} reach considerably with respect to competing experiments.

The measurement of P-wave quarkonium production with the CMS detector is conducted through the radiative decays into S-wave states, involving soft photons that are reconstructed through photon conversions in the inner silicon tracker, allowing for a very good photon momentum resolution, albeit burdened by a rather small photon conversion reconstruction efficiency, associated with large systematic uncertainties. Therefore, the analyses of P-wave quarkonium production have been limited to the measurement of the relative prompt χ_{c2}/χ_{c1} [9] and $\chi_{b2}(1P)/\chi_{b1}(1P)$ [10] production cross section ratios, at $\sqrt{s}$ =7 TeV and $\sqrt{s}$ =8 TeV, respectively, as the systematic uncertainties on the photon conversion reconstruction efficiency cancel almost entirely in these measurements.

Figure 1 shows results of p_{T} differential production cross sections at mid-rapidity of several S-wave and P-wave quarkonium states from the CMS and ATLAS experiments, as function of p_{T}/M_{Q}, with M_{Q} the mass of the respective quarkonium state. Above a certain value of p_{T}/M_{Q}, the

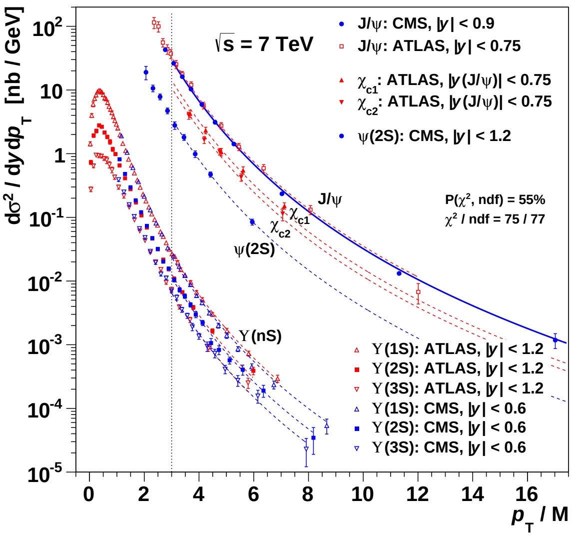

Figure 1: p_T differential production cross sections at mid-rapidity for several quarkonium states from the CMS and ATLAS Collaborations, plotted as function of p_T/M_Q. A fitted empirical power-law function is also shown, with different normalization parameters for each state [11].

shapes of the cross sections are very similar, as can be appreciated by an empirical function fitted to one of the data sets, shifted vertically by a normalization factor for each state, resulting in a good description with a large χ^2-probability [11].

Given that the individual measurements shown in this figure include both S-wave and P-wave states, all affected by very different feed-down contributions of heavier quarkonium states, this study suggests that quarkonium production should be rather simple and very similar for all quarkonium states, dominated by one single production mechanism in all cases, required to be a color-octet mechanism, given that the color-singlet mechanisms depend on the quantum numbers of the quarkonium states.

3. Quarkonium polarization measurements

The measurement of the polarization of $J^{PC} = 1^{--}$ vector-quarkonium states is conducted through the analysis of the decay angular distribution of the dimuon decay. The most general observable parity-conserving decay angular distribution of the dimuon decay can be written as [2]

$$W(\cos\vartheta, \varphi|\vec{\lambda}) = \frac{3}{4\pi(3+\lambda_\vartheta)}(1+\lambda_\vartheta\cos^2\vartheta + \lambda_\varphi\sin^2\vartheta\cos 2\varphi + \lambda_{\vartheta\varphi}\sin 2\vartheta\cos\varphi), \qquad (3.1)$$

with ϑ and φ the polar and azimuthal angles, respectively, of the positive muon, with respect to the chosen quantization axis z in the production plane in the quarkonium rest frame, and $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ the frame-dependent anisotropy parameters.

Following recipes of improved analysis methodologies for the measurement of quarkonium polarization [2], CMS has measured the full angular distribution by measuring all frame-dependent anisotropy parameters $\vec{\lambda}$, in three polarization frames, complemented by the measurement of the frame-invariant quantity $\tilde{\lambda}$ [12], for all S-wave quarkonium states, the charmonium J/ψ and ψ' [13],

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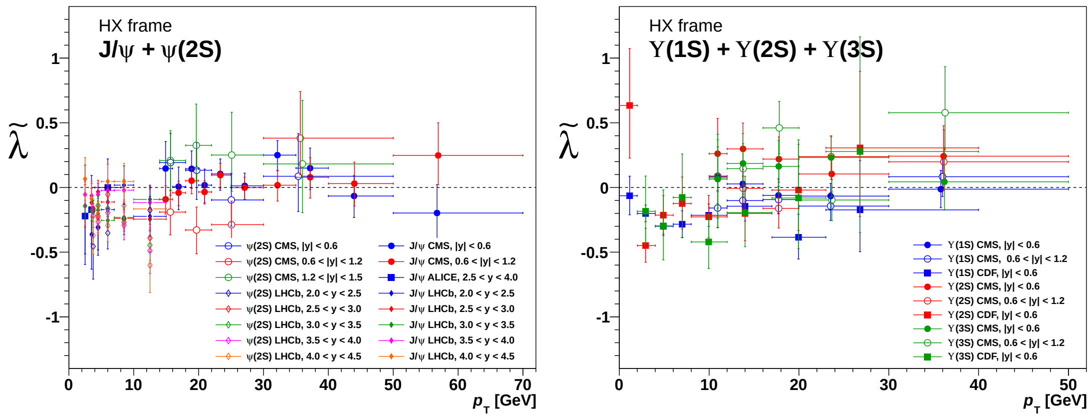

Figure 2: Results for the parameter $\tilde{\lambda}$ as function of p_T, for the S-wave charmonium (left) and bottomonium (right) states, as measured by the ALICE [15], CDF [16], CMS [13, 14] and LHCb [17, 18] Collaborations in several rapidity ranges, as indicated in the legends.

and the bottomonium $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ [14] states. To detect possible kinematic dependencies of the polarization observables, as well as to avoid experimental pitfalls [2], the analyses are conducted in fine cells of p_T and $|y|$.

Despite the expectations based on state-of-the-art NRQCD calculations [1], no significant polarizations are observed in these measurements. Figure 2 shows a comparison of measured p_T dependencies of the frame-invariant parameter $\tilde{\lambda}$ for all S-wave quarkonium states, as measured by various experiments, in several rapidity ranges. The measurements of quarkonium polarization in the LHC-era show a consistent experimental situation: None of the S-wave charmonium or bottomonium states show strong polarizations, and no dependencies on p_T or rapidity are observed.

The straight-forward explanation for these findings is to assume that quarkonium production is dominated by the unpolarized intermediate ${}^1S_0^{[8]}$ color-octet $Q\bar{Q}$ state (see below).

4. Comparison to NRQCD calculations

The NRQCD factorization approach is an effective field theory approximating full QCD in the limit of infinite quark masses [1]. Quarkonium production can be separated in the perturbative production of the initial $Q\bar{Q}$ pair, followed by the non-perturbative hadronization into the quarkonium state. Given the so-called velocity-scaling rules and the small relative quark velocities, only few intermediate $Q\bar{Q}$ states are expected to contribute to S-wave quarkonium production, the ${}^3S_1^{[1]}$ color-singlet state, and the ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ color-octet states. The relative importance of the individual production channels is determined by the long-distance matrix elements (LDMEs), which are not accessible by model calculations and are therefore estimated by fits to experimental data.

Several analysis teams have conducted NRQCD calculations at next-to-leading order (NLO), estimating the LDMEs from data, using various different data sets characterized by different kinematic regions, differing assumptions on the individual production channels, and different feed-down considerations. The LDME fit results – and therefore the physics conclusions – of the individual analyses are rather different, as can be appreciated by Fig. 3, comparing the CMS polarization measurements to the individual NRQCD polarization calculations of Refs. [19, 20, 11]. There

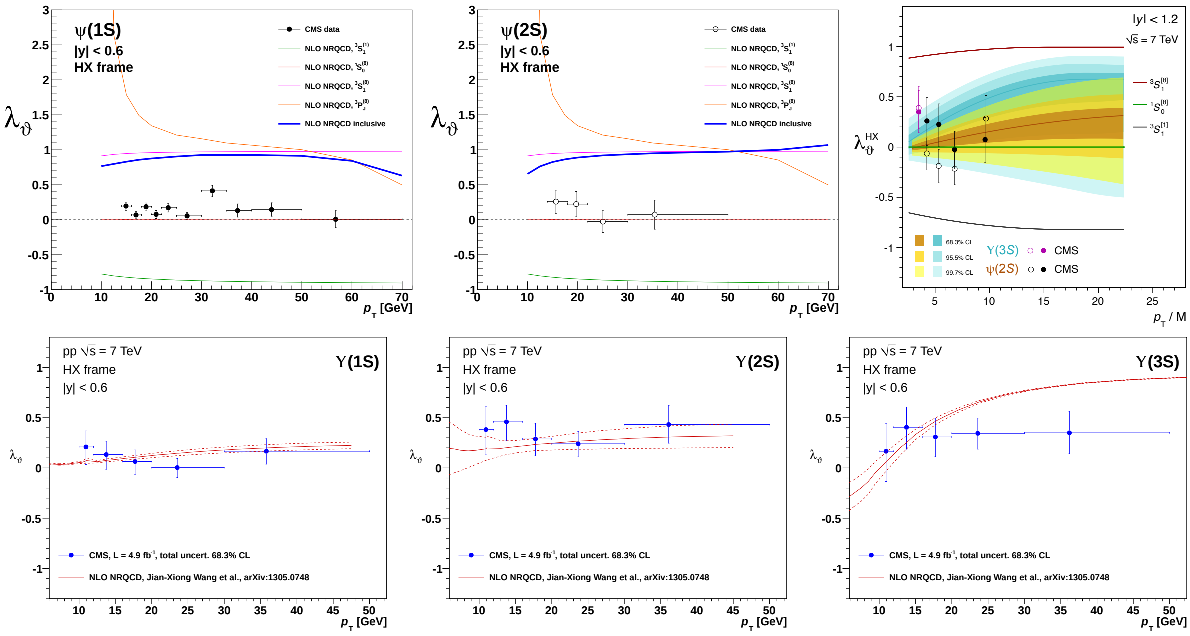

Figure 3: Polarization parameter λ_ϑ^{HX} at mid-rapidity as function of p_T, as measured by CMS for all S-wave quarkonium states, compared to various NRQCD calculations.

are large tensions between the CMS measurements and the calculations of Ref. [19] (top left and top middle panels) and Ref. [20] (bottom panels). The J/ψ calculations have to be interpreted with care, as they do not include feed-down decays. The tensions are especially serious for the highest mass S-wave ψ' and $\Upsilon(3S)$ states, caused by the dominance of the transversely polarized ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ color-octet states in these analyses.

A new, data-driven phenomenological analysis [11], moving the polarization observable to the center of the study and removing low p_T data from the fits – as the theory calculations cannot be expected to be reliable in this region – is able to reconcile data and NRQCD calculations (see top right panel) for both ψ' and $\Upsilon(3S)$ cross sections and polarizations, finding that the intermediate ${}^1S_0^{[8]}$ $Q\bar{Q}$ state dominates, as hinted by the unpolarized LHC data.

5. Summary

CMS has contributed vastly to the LHC quarkonium physics program, by measuring prompt double differential cross sections and polarizations of all five S-wave quarkonium states, as well as prompt cross section ratios in the χ_c and $\chi_b(1P)$ systems. The similar shapes of their cross sections suggest that all quarkonia are produced dominantly by one color-octet process. The absence of polarization of the S-wave states suggests that this dominant color-octet process proceeds via the intermediate ${}^1S_0^{[8]}$ $Q\bar{Q}$ state.

Several further related results will be published based on 7 TeV and 8 TeV data. Furthermore, the LHC run 2 at 13 TeV will allow CMS to further extend the p_T reach of the quarkonium production and polarization measurements.

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