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Study of the production of heavy quarkonium states at CMS

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Summary. — Studies of the production of heavy quarkonium states are fundamental to improve our understanding of QCD and hadron formation. In fact, the heavy quark masses allow the application of theoretical tools that are relatively insensitive to non-perturbative effects. In this field, the CMS experiment at LHC can give significant contributions. Thanks to a specific dimuon trigger strategy, CMS collected large samples of quarkonium states which decay to dimuons from pp collisions at 7, 8 and 13 TeV. Some of the latest CMS quarkonium production results are presented in this paper, such as the measurement of differential production cross-sections of J/ψ and $\psi(2S)$ charmonium and $\Upsilon(nS)$ $(n = 1, 2, 3)$ bottomonium states in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$, on data samples corresponding to an integrated luminosity of $2.3\,\text{fb}^{-1}$ for the J/ψ and $2.7\,\text{fb}^{-1}$ for the other mesons. Each double-differential cross-section is measured as a function of rapidity and transverse momentum.

1. – Introduction

High-energy proton-proton and nucleus-nucleus collisions at CMS gave access to a large sample of quarkonia, that is heavy quark-antiquark bound states. One of the best established and most tested theoretical frameworks to describe quarkonium production is nonrelativistic quantum chromodynamics (NRQCD) [1-3]. According to this theory, the quarkonium production mechanism can be factorized in two distinct phases. In the first phase, the $q\bar{q}$ pair is produced in a given spin and orbital angular momentum state, which is not necessarily the same as the observed final state. The colour configuration as well can be either a colour singlet or a colour octet. The corresponding parton-level cross-sections, usually called short-distance coefficients (SDCs), are functions of the kinematics of the state and can be calculated perturbatively, presently up to next-to-leading order (NLO) [4-7]. Afterward, the system undergoes a transition to a colour singlet state through a nonperturbative hadronization process, with the emission of one ore more soft photons. The transition probabilities are in this case determined by process-independent long-distance matrix elements (LDMEs) [4-9]. Unlike the SDCs, the LDME are not calculable at present, and have to be extracted from fits to experimental data.

Experiments at CERN LHC have measured the differential cross-sections of several S-wave quarkonium states, including J/ψ, $\psi(2S)$, $\Upsilon(nS)$ ($n = 1, 2, 3$), at the centre-of-mass energies of 2.76, 7 and 8 TeV [10-14]. Nevertheless, further experimental work and measurements at higher energies can help in improving the fits and determining more precisely the weights of the LDMEs. In the following, the measurement of double differential cross-sections of the aforementioned five S-wave quarkonium states in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ at the CMS detector at the LHC is described.

2. – CMS results

The measurement of the differential cross-sections has been performed by the CMS Collaboration using data collected at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $2.3\,\text{fb}^{-1}$ for the J/ψ and $2.7\,\text{fb}^{-1}$ for the other mesons. The lower value for the J/ψ is due to a trigger pre-scaling, which was applied during part of the data taking in order to reduce the trigger rate. The quarkonium states are reconstructed through their leptonic decay into muon pairs. The trigger used at software level is a dimuon trigger requiring the pairs of opposite-charge muons to have an invariant mass in the regions 2.9–3.3, 3.35–4.05 or 8.5–11 GeV for the J/ψ, $\psi(2S)$ and $\Upsilon(nS)$, respectively. A minimum p_T of 9.9 GeV for the J/ψ and 7.9 GeV for the remaining states is required for the dimuon system. The dimuon rapidity is restricted to $|y| < 1.25$. Further criteria on muons p_T and η, and on the tracks impact parameter are applied in the offline selection.

The product of the branching ratio of quarkonia to muon pairs, $\mathcal{B}(\mathcal{Q} \rightarrow \mu^+\mu^-)$, and the double-differential production cross-section, $\mathrm{d}^2\sigma/(\mathrm{d}p_T\mathrm{d}y)$, in bins of p_T and rapidity y, is given by

$$\mathcal{B}(\mathcal{Q} \rightarrow \mu^+\mu^-)\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}y} = \frac{N(p_T, y)}{\mathcal{L}\Delta y \Delta p_T}\left\langle \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)} \right\rangle, \tag{1a}$$

where $N(p_T, y)$ is the number of prompt signal events in the bin, $\mathcal{L}$ is the integrated luminosity, Δy and Δp_T are the bin widths, and $\langle 1/(\epsilon(p_T, y)\mathcal{A}(p_T, y))\rangle$ represents the average of the product of the inverse acceptance and the efficiency for all the events in the bin. The separation of the nonprompt components of the J/ψ and $\psi(2S)$ mesons (*i.e.*, the ones originating from b hadrons decay) exploits their different decay length $l = L_{xy} \cdot m/p_T$, where L_{xy} is the distance measured in the transverse plan between the average location of the luminous region and the fitted position of the dimuon vertex, m is the mass of the J/ψ ($\psi(2S)$) [15], and p_T is the transverse momentum of the dimuon candidate. The acceptance for a given ($p_T, |y|$) range is defined as the ratio of the number of signal events passing the kinematic selection criteria defined for this study and the total number of simulated events in that p_T and $|y|$ range. Since the acceptance is dependent on the quarkonium polarization, it is here derived for the unpolarized scenario (which is close to experimental measurements within the uncertainties), while multiplicative correction factors have been calculated for the other polarization options.

The extraction of the signal yields proceeds through an extended unbinned maximum-likelihood fit to the dimuon invariant mass spectrum for the $\Upsilon(nS)$ states, and to the dimuon invariant mass and decay length distributions for the J/ψ and $\psi(2S)$ mesons. The measured differential cross-sections times dimuon branching ratios are shown in fig. 1.

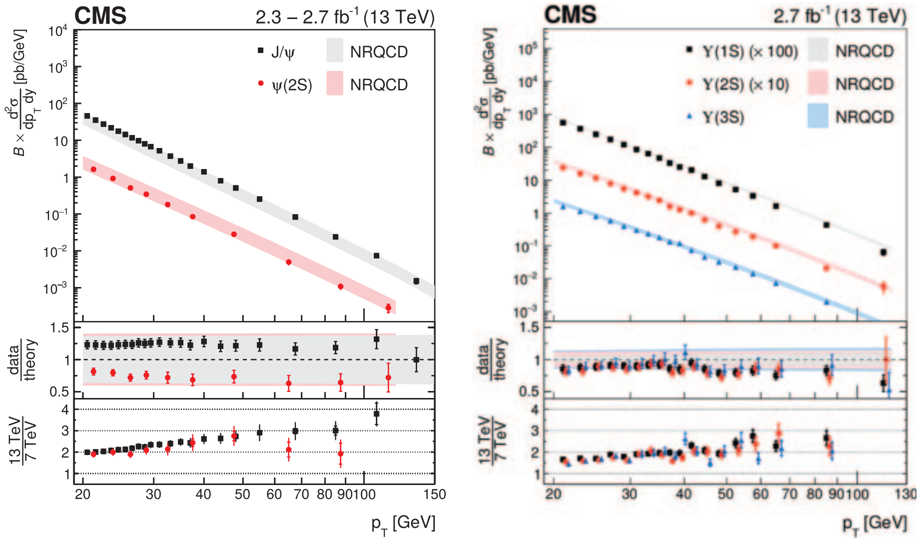

Fig. 1. – Product of the measured double-differential cross-sections times dimuon branching ratios, for prompt J/ψ and $\psi(2S)$ (left) and $\Upsilon(nS)$ (right) mesons, as a function of p_T, for $|y| < 1.2$ [16]. The dimuon decay is assumed to be unpolarized. The inner vertical bars on the data points represent the statistical uncertainties, while the statistical+systematic uncertainties are represented by the outer bars. For most of the points, the uncertainties are comparable to the size of the symbol. The experimental measurements are compared to the NLO NRQCD predictions (shaded bands) [17, 18]. The middle panel shows the ratios of measurement to theory. The widths of the bands represent the theoretical uncertainties, summed in quadrature with the uncertainty on the dimuon branching ratio [15]. In the lower panels, the ratios of the measurements at $\sqrt{s} = 13$ TeV with the ones at $\sqrt{s} = 7$ TeV are presented [19, 20].

3. – Conclusions

The double-differential production cross-sections of J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ ($n = 1, 2, 3$) have been measured, using their dimuon decay mode, in pp collisions at $\sqrt{s} = 13$ TeV with CMS. The experimental results are compared to the theoretical predictions from NRQCD, thus helping to test this model and providing further input to constrain the theoretical parameters.

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