EPJ Web of Conferences 80, 00006 (2014)
DOI: 10.1051/epjconf/20148000006

Quarkonium production in pp collisions with the CMS detector

Alexis Pompili[1,2,a] (on behalf of CMS Collaboration)

[1] *Dipartimento Interateneo di Fisica, Universitá degli Studi di Bari, via Amendola 173, 70126 Bari, Italy*
[2] *Istituto Nazionale di Fisica Nucleare, Sezione di Bari, via Orabona 4, 70125 Bari, Italy*

Abstract. The studies of the inclusive production of heavy quarkonium states at LHC are very important to improve our understanding of QCD and hadron formation, given that the heavy-quark masses allow the application of theoretical tools less sensitive to nonperturbative effects. The prompt cross sections and polarizations measured by CMS and the other LHC experiments are presented for the five S-wave states J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ ($n = 1, 2, 3$) and discussed especially in comparison to the theoretical predictions provided by Non Relativistic QCD.

1 Introduction

Quarkonia are bound states of an heavy-quark and an heavy-antiquark ($c\bar{c}$, $b\bar{b}$) and exist in "families" of several colorless states (neutral mesons). Quarkonium spectra and decays are well understood below open charm and open beauty thresholds. Quarkonium production is still an active field of research; production rates at the LHC are rather high and LHC can be considered a "quarkonium factory". Quarkonium production occurs through two mechanisms: a) *prompt* production, *direct* or *feed-down* from higher quarkonium states, b) *non-prompt* production, from B decays (for charmonia only). The study of quarkonium prompt production is suited to understand how quarks combine into a bound state (the hadron). This mechanism is still not easy to understand, likely because it is a part of the non-perturbative QCD sector.

Properties of QCD can be probed by LHC experiments, in different new kinematic regions, through several quarkonium production measurements including production cross sections (discussed in section 2) and polarizations (discussed in section 3). The polarization is sensitive to the hadroproduction mechanism and therefore is crucial for the theoretical understanding. Many extensive and detailed reviews about these topics are available and, among them, [1][2][3][4] are certainly useful to enter this field.

2 Quarkonium production

In the $Q\bar{Q}$ center-of-mass frame quarks can be considered not relativistic; being v the velocity of the heavy-quark in this frame, $\nu = v/c \ll 1$ is a better approximation for $b\bar{b}$ than $c\bar{c}$. The non-relativistic QCD (NRQCD) is an effective field theory that treats heavy quarkonia as non-relativistic systems [5]. The heavy-quark mass is $m_Q \gg \Lambda_{QCD}$ which provides a natural boundary between short- and

[a] e-mail: alexis.pompili@ba.infn.it

long-distance QCD. This allows the inclusive quarkonium production to be factorized in two distinct steps. In the first step the $Q\bar{Q}$ pair should be produced in the regime of perturbative QCD, whereas in the second step a bound state driven by non-perturbative QCD should be formed. In this NRQCD factorization conjecture the inclusive cross section for producing the quarkonium state H with enough large momentum transfer p_T is the sum of short-distance coefficients (SDCs, σ_n) multiplied by long-distance matrix elements (LDMEs, P_n)

$$\sigma(A + B \to H + X) = \sum_n \sigma_n \cdot P_n = \sum_n \sigma(A + B \to [Q\bar{Q}]_n + X) \cdot P([Q\bar{Q}]_n \to H)$$

where the sum is over the states with $n = {}^{2S+1}L_J^C$ since the $Q\bar{Q}$ pair can be, at short distances, produced in a state n with definite spin S, angular momentum L, total angular momentum J and color $C = 1, ..., 8$.

The SDCs are inclusive perturbative QCD cross sections of partonic processes to form the $Q\bar{Q}$ pair in state n (convoluted with probability density functions); they are process- and kinematics-dependent functions calculated perturbatively as expansions in α_s. On the other hand the LDMEs represent the probability of the $Q\bar{Q}$ pair in state n to evolve into the quarkonium final state H; they are expected to be universal constants, i.e. the same in pp collisions, e^+e^- collisions and in general for any collision process and independent of kinematics variables (such as p_T and the rapidity y). The LDMEs are determined by fits to experimental data and their relative importance should depend on v-scaling rules.

Theoretical predictions are organized as double expansions in α_s and v. In the current NRQCD phenomenology the truncation of v-expansion for spin-triplet S-wave states (J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$) includes four terms: the Color Singlet (CS) term (${}^3S_1^{[1]}$) and three Color Octet (CO) terms (${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_{J=0,1,2}^{[8]}$), all of relative order $O(v^4)$ with respect to the CS term. The CS term is characterized by a suppression of powers of α_s thus making important the CO channels despite of their suppression by powers of v. The old color singlet model [6] assumed that the initial $Q\bar{Q}$ pair and the final quarkonium H have the same quantum numbers, whereas NRQCD predicts the existence of intermediate CO states that subsequently evolve into color singlet quarkonia by non-perturbative emission of soft gluons.

NRQCD provides [7][8] good consistency in the fit of the differential production cross sections as a function of p_T when including color octet terms and next-to-leading order (NLO) corrections in α_s; the fit function consists in a superposition of CS and CO SDCs and the CS contribution is fixed while the CO terms is characterized by fixed shape but floating normalizations (represented by the LDMEs).

Fig.1 that shows a compilation [1] of mid-rapidity double differential cross sections for the production of 7 different quarkonia as a function of p_T/M. All shapes are well described by a single empirical power-law function for $p_T/M > 3$, a cut justified by the fact that NRQCD calculations are not expected to reproduce the measurements at low p_T values. The p_T/M scaling behaviour, common to five S-wave states and two P-wave states characterized by different feed-down contamination levels, suggests a simple composition of processes dominated by one single mechanism. In particular one single CO term should dominate their production and this could be ${}^1S_0^{[8]}$ if the NRQCD fit would start at $p_T/M > 3$ as argumented in [1].

This scaling behaviour needs to be confirmed with more accurate data up to higher p_T values since the fits also suggest that ${}^3S_1^{[8]}$ could become dominant at higher momenta. During the preparation of this proceeding CMS made available updated production measurements, based on the full 2011 dataset [14], covering a broader p_T range extending from 15 to 120 GeV for the J/ψ and up to 100 GeV for the $\psi(2S)$.

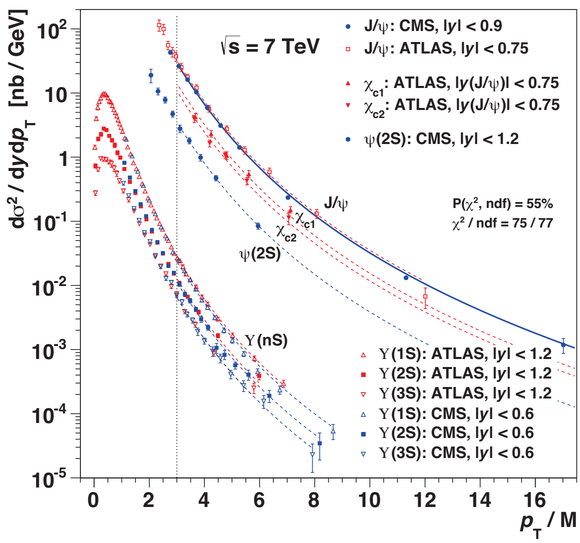

Figure 1. This compilation [1] summarizes results from CMS [9][10] and ATLAS [11][12][13]. The transverse momentum p_T is mass rescaled to equalize the kinematics' effects of different average parton momenta and phase spaces. The solid curve represents the fit to CMS J/ψ data whereas the dashed curves are replicas with adjusted normalizations.

3 Quarkonium polarization

The polarization of a vector meson decaying into a lepton pair is reflected in the leptons' angular distributions, specified in terms of the spherical angles θ and ϕ of the momentum vector of the positively charged lepton in the meson rest frame. A polarization frame must be chosen to define these two angles: θ is the polar angle with respect to the spin-quantization z-axis, whereas ϕ is the azimuthal angle with respect to the x-axis that lies, together with the z-azis, in the collision plane (defined by the momentum vectors of the colliding hadrons boosted in the meson rest frame). However there is not an unique choice of the polarization z-axis in the collision plane and, correspondingly, at least three conventional reference frames can be introduced [3]: a) center-of-mass helicity frame (HX), b) Collins-Soper frame (CS), and c) perpendicular helicity frame (PX).

The most general 2D angular distribution for the dileptons from the decay of a vector meson is specified by a set of three polarization parameters, $\vec{\lambda} \equiv (\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$ and can be expressed, aside from a normalization factor, as follows:

$$W \equiv \frac{d^2N}{d(cos\theta)d\phi} \propto \frac{1}{(3+\lambda_\theta)}(1+\lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos2\phi + \lambda_{\theta\phi} sin2\theta cos\phi)$$

Two extreme angular decay distributions obtainable by ($\lambda_\theta = \pm 1, \lambda_\phi = 0, \lambda_{\theta\phi} = 0$) represent transverse ($J_z = \pm 1$) and longitudinal ($J_z = 0$) polarization, respectively. Thus λ_θ measures the degree of polarization with respect to the spin-quantization axis. Theoretically this parameter can be expressed [4] as a function of the cross sections for the two transverse states (σ_T) and the longitudinal state (σ_L) as follows: $\lambda_\theta = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$. Generally $\vec{\lambda}$ can be expressed as a function of components of the $p\bar{p} \to H + X (H \equiv J/\psi, \psi(2S), ...)$ differential cross sections given in terms of PDFs and partonic spin density matrix elements.

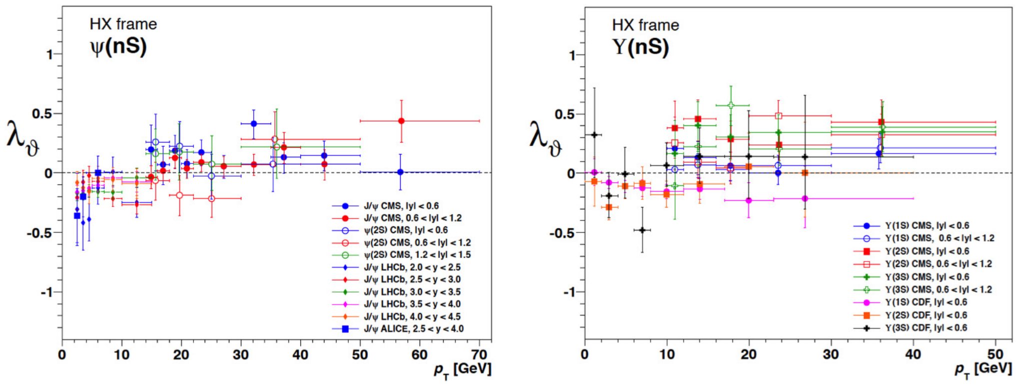

Figure 2. This compilation [1] summarizes polarization results from CMS [16][17], LHCb[18], Alice[19] and CDF[20]: λ_θ is measured the HX frame, as a function of p_T, in different rapidity intervals.

Each NRQCD term is characterized by a specific polarization: at NLO, ${}^3S_1^{[1]}$ is longitudinal, ${}^1S_0^{[8]}$ isotropic, ${}^3S_1^{[8]}$ transverse at high p_T values and ${}^3P_J^{[8]}$ hyper-transverse at high p_T.

As explained in [3] the observed polarization depends on the polarization frame and the polarization can be fully determined when either
a) both the polar and azimuthal components of angular distribution W are known (λ_θ and λ_ϕ), or
b) a single polarization parameter is measured in at least two complementary polarization frames (for instance λ_θ in the HX and CS frames).
On the other hand, being the shape of the angular distribution frame-independent, it can be characterized by a frame-invariant combination of the parameters such as $\tilde{\lambda} = (\lambda_\theta + 3\lambda_\phi) / (1 - \lambda_\phi)$ [15].

The three polarization parameters $\vec{\lambda}$ and $\tilde{\lambda}$ have been measured by CMS [16][17] in three different frames (HX, CS, PX) for the 5 S-wave states as a function of transverse momentum and rapidity. No evidence of strong longitudinal or transverse polarizations has been observed, independently of the level of feed-down contributions (with unknown polarizations) characterizing differently these states. This result holds for any parameter in any frame; moreover there is a good agreement among the $\tilde{\lambda}$ values in the three polarizations frames thus showing that the results are consistent.

Fig.2 presents a compilation [1] of λ_θ measurements in the HX frame at LHC, showing that all LHC results are compatible with each other. The polarizations cluster around the unpolarized limit with
a) no significant dependencies on p_T or y,
b) no strong changes among states differently affected by P-wave feed-down and the $\psi(2S)$ not affected at all,
c) no evident differences between $c\bar{c}$ and $b\bar{b}$ states.
This result again suggests [1] that all quarkonia are predominantly produced by a single mechanism and that, given the unpolarized result, the dominant contribution must come from ${}^1S_0^{[8]}$. New p_T-extended polarization measurements would allow to test if polarization turns to transverse accordingly to a production dominated at higher momenta by the ${}^3S_1^{[8]}$ contribution.

Figg.3 and 4 show the λ_θ parameter measured in the HX frame by CMS [16][17] in comparison to NLO NRQCD predictions [7][8], for the 5 S-wave states.

In Fig.3 the theoretical calculations use a global fit of CO LDMEs to photo- as well as hadro-production data (polarization results are not considered); their predictions only consider direct production and therefore the comparison makes sense only for $\psi(2S)$ data since it should not suffer from

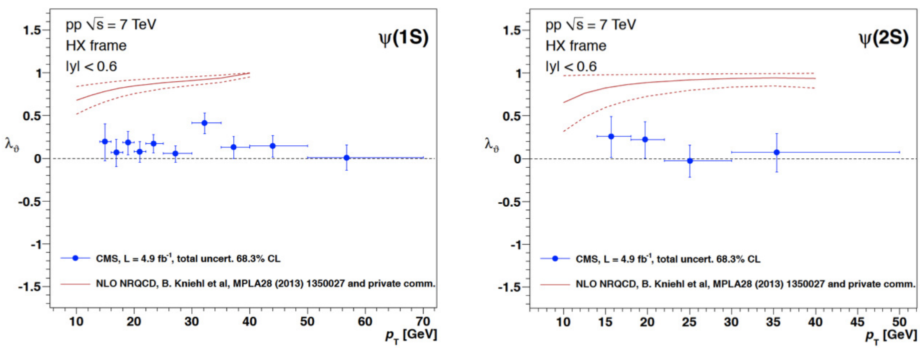

Figure 3. λ_θ parameter for J/ψ (left) and $\psi(2S)$ (right) states measured by CMS [16] in the HX frame, as a function of dimuon p_T for $|y| < 0.6$, compared to NLO NRQCD predictions [7].

feed-down contributions with unknown polarizations. The disagreement between theoretical and experimental results is well evident.

In the theoretical calculations of Fig.4 CO LDMEs are left as free parameters in the fit to hadroproduction data; these calculations include the feed-down contributions to $\Upsilon(1S)$ and $\Upsilon(2S)$ and the extra adjustable fit parameters (LDMEs of $\chi_{bJ}(nP)$ states) help reaching compatibility with data. The production cross section ratio $\sigma(\chi_{b2}(1P))$ / $\sigma(\chi_{b1}(1P))$ (corrected for the ratio of the branching fractions of $\chi_{b1,2}(1P) \to \Upsilon(1S)\gamma$) has been recently measured by CMS [21] and can be useful to constrain the CO LDMEs.

The $\Upsilon(3S)$ state instead is assumed [8] to be exclusively directly produced, thus allowing less freedom in the fit and a certain disagreement between theoretical predictions and experimental measurements can be observed. During the preparation of this proceeding LHCb has revealed the observation that about 50% of $\Upsilon(3S)$ mesons are not produced directly but they originate from the radiative decay of $\chi_b(3P)$ mesons [22]. Thus the assumption of a negligible feed-down contribution to the prompt production of $\Upsilon(3S)$ needs to be revisited.

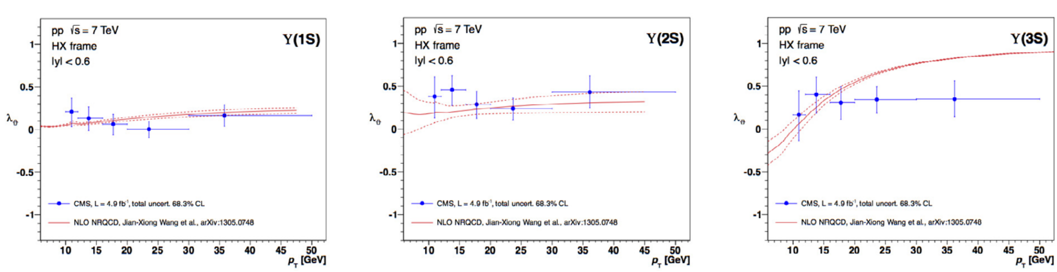

Figure 4. λ_θ parameter for $\Upsilon(1S)$ (left), $\Upsilon(2S)$ (center) and $\Upsilon(3S)$ (right) states measured by CMS [17] in the HX frame, as a function of dimuon p_T for $|y| < 0.6$, compared to NLO NRQCD predictions [8].

4 Conclusions

Cross section measurements at LHC are dominated by color octet production. In the hadron formation the $Q\bar{Q}$ bound states seem to be preferably formed by two heavy-quarks of different colors and smaller relative angular momentum and spin, later evolving into the physical color singlet quarkonia. Polarization measurements show no relevant longitudinal or transverse polarization for S-wave states, in disagreement with NLO NRQCD predictions. Discrepancy between theory and experiment with respect to polarization deserves further investigation both theoretically and experimentally.

Theory-data comparisons should be reconsidered including polarization data in global NRQCD analyses of production. In the experimental field it is essential to perform measurements with smaller uncertainties and extend p_T reach thus testing the NRQCD validity domain. It would be useful for future measurements to separate the feed-down contributions from direct production. Challenging measurements of production and polarization for the χ_{cJ} and χ_{bJ} P-wave states would provide valuable additional tests.

References

[1] P. Faccioli *et al.*, Phys. Lett. B **736**, 98 (2014).

[2] G.T. Bodwin *et al.*, arXiv:1307.7425, Conference C13-07-29.2 (Snowmass 2013)

[3] P. Faccioli *et al.*, Eur. Phys. J. C **69** (2010) 657

[4] E. Braaten and J. Russ, arXiv:1401.7352 (for Vol. 64 of the Annual Review of Nucl. and Part. Science)

[5] G.T. Bodwin *et al*, Phys. Rev. D **51** (1995) 1125

[6] E.L. Berger and D.L. Jones, Phys. Rev. D **23** (1981) 1521;
R. Baier and R. Ruckl, Phys. Lett. B **102**, 364 (1981).

[7] M. Butenschoen and B.A. Kniehl, Phys. Rev. Lett. **108** (2012) 172002, later in Mod. Phys. Lett. A **28** (2013) 1350027, and private communication

[8] B. Gong *et al.*, Phys. Rev. Lett. **112** (2014) 032001

[9] CMS Collaboration, JHEP **02** (2012) 011

[10] CMS Collaboration, Phys. Lett. B **727**, 101 (2013).

[11] ATLAS Collaboration, JHEP **07** (2014) 154

[12] ATLAS Collaboration, Nucl. Phys. B **850** (2011) 387

[13] ATLAS Collaboration, Phys. Rev. D **87** (2013) 052004

[14] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH14001/

[15] P. Faccioli *et al.*, Phys. Rev. Lett. **105** (2010) 061601

[16] CMS Collaboration, Phys. Lett. B **727** (2013) 381

[17] CMS Collaboration, Phys. Rev. Lett. **110** (2013) 081802

[18] LHCb Collaboration, Eur. Phys. J. C **73** (2013) 41

[19] Alice Collaboration, Phys. Rev. Lett. **108** (2012) 082001

[20] CDF Collaboration, Phys. Rev. Lett. **108** (2012) 151802

[21] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH13005/

[22] LHCb Collaboration, arXiv:1407.7734 (2014)