Heavy-quark production in small collision systems

M. Pennisi(1)(2) on behalf of the ALICE collaboration
(1) *INFN, Sezione di Torino - Torino, Italy*
(2) *Dipartimento di Fisica, Università di Torino - Torino, Italy*

Summary. — Quarkonium measurements in proton-proton (pp) collisions represent a fundamental tool for studying quantum chromodynamics due to the involvement of both perturbative and non-perturbative regimes and their interplay in the resonance formation process. The ALICE experiment has measured quarkonia in various collision systems at the LHC through their dilepton decays. Quarkonia can be reconstructed in the e^+e^- decay mode at midrapidity ($|y| < 0.9$) in the central barrel, and at forward rapidity ($2.5 < y < 4.0$) in the muon spectrometer, through their $\mu^+\mu^-$ decay channel. This contribution will summarize some recent ALICE quarkonium measurements in small collision systems, compared with available theoretical models.

1. – Introduction

Quarkonium (i.e. a bound state of charm or beauty quark pairs), and in particular its production process in hadronic collisions, represents an excellent probe to understand Quantum Chromodynamics (QCD) better. Heavy-quark production occurs in initial hard scatterings, where the large mass of the quarks sets the hard scale, allowing to compute the cross section using perturbative QCD (pQCD) calculations. On the contrary, the hadronization (i.e. the binding of quark and anti-quark in a colorless state) is a non-perturbative process. A plethora of theoretical models, mainly differing in the treatment of these two scales (see Ref. [1] for an overview), try to reproduce the experimental observations. In addition, at LHC energies, multi-parton interactions (MPI) occur frequently, generating high-multiplicity events. Studying quarkonium production as a function of charged particle multiplicity helps to understand the interplay between hadronization and MPIs. Apart from being of fundamental importance for the aforementioned reasons, quarkonium production in small collision systems is used as a reference for measurements in heavy-ion collisions, in which the formation of a hot and dense quark–gluon plasma (QGP) is expected. With its unique geometry, the ALICE experiment provides the opportunity to study quarkonia at both midrapidity ($|y| < 0.9$), in the dielectron decay channel, and forward rapidity ($2.5 < y < 4.0$), in the dimuon decay channel. The main ALICE detectors to study quarkonia at midrapidity are the Inner Tracking System (ITS), which serves for vertexing and tracking purposes, and also for measuring charged particle multiplicity, and the Time Projection Chamber (TPC), which is used for tracking and particle identification by measuring the specific energy loss. The vertexing and tracking capabilities of these two detectors allow us to separate at midrapidity the prompt from the non-prompt charmonium components, i.e. the former being charmonia produced directly by the hadronization of charm quark pairs and the latter those produced by the decay of beauty hadrons (feed-down). At forward rapidity, inclusive quarkonia (during Run 1 and 2) are reconstructed using the Muon Spectrometer, which is composed of a front absorber, needed to filter out the hadronic background of light-flavor hadrons (mainly π and K), a dipole magnet, a muon tracker and a muon trigger system, which serves also for dimuon triggers. The minimum bias trigger, as well as the beam-gas background rejection, is provided by V0 detectors, which cover the pseudorapidity intervals $-3.7 < \eta < -1.7$ (V0C) and $2.8 < \eta < 5.1$(V0A). A detailed description of the ALICE apparatus can be found in [2].

2. – Quarkonium and heavy-quark production results in pp

The cross section for inclusive p_T-differential quarkonium production at forward rapidity (left panel for J/ψ [3], right panel for Υ(1S)) are shown in Fig.1 at various collision energies. For the J/ψ results, the ratios of cross sections at various collision energies

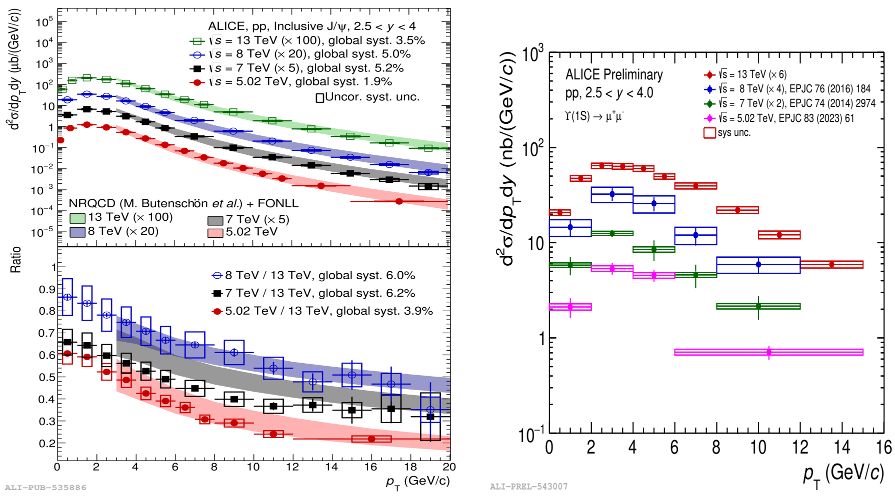

Fig. 1. – Inclusive p_T-differential quarkonium cross sections (left panel for J/ψ, right panel for Υ(1S)), measured in pp collisions at $\sqrt{s}$ = 5.02, 7, 8 and 13 TeV. The J/ψ results have been compared with NRQCD [4] calculations, coupled with FONLL[6] to include the non-prompt J/ψ contribution from b-hadron decays.

with respect to those at $\sqrt{s}$ = 13 TeV are also shown. The data are compared with theoretical calculations from Non-Relativistic QCD (NRQCD) [4] (shown in Fig.1 left) and Improved Color Evaporation Model (ICEM) [5] (not shown). For both models, the feed-down from beauty hadrons is considered using Fixed Order plus Next-to-Leading Logarithms (FONLL) [6] calculations. Both models encounter difficulties for reproducing all the cross section ratios among different energies but are fairly compatible considering the experimental and theoretical uncertainties. ALICE has also provided J/ψ production cross section measurements at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV (see Fig. 3 and 4 of [7]), separating the prompt and the non-prompt components. For the prompt J/ψ, NRQCD and ICEM (not shown) calculations well reproduce data, but the current uncertainties of the calculations do not allow for discrimination among models. For the non-prompt J/ψ cross section, the FONLL calculations are in fair agreement with the data.

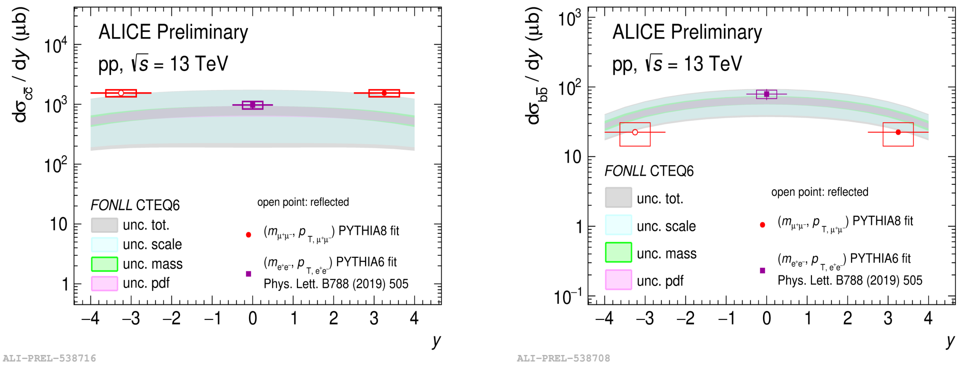

Fig. 2. – Preliminary y-differential charm (left) and beauty (right) cross sections measured in pp collisions at $\sqrt{s}$ = 13 TeV. The red markers represent the new ALICE measurement at forward rapidity, obtained with measuring dimuons in $4 < m_{\mu\mu} < 9$ GeV/c^2, while the midrapidity result was obtained with the dielectron measurement [8] (purple markers). Results are compared to FONLL calculations [6].

In addition, the muon pair continuum was recently used to measure the total charm and beauty cross sections via semileptonic decays of charm and beauty hadrons at forward rapidity in pp collisions at $\sqrt{s}$ = 13 TeV. The results were obtained by studying the dimuon invariant mass spectrum in the interval $4 < m_{\mu\mu} < 9$ GeV/c^2 and are shown in Fig.2. These results complement previous measurements obtained by ALICE in the dielectron channel [8] at midrapidity. Both results have been compared with FONLL predictions, showing a good agreement between data and the model within the largely involved uncertainties.

The prompt and non-prompt J/ψ yields as a function of $z_{J/\psi}$ (*i.e.* the fraction of the jet momentum carried by the J/ψ) in charged jets at the collision energy of $\sqrt{s}$ = 13 TeV have been measured at midrapidity, and the corresponding results are shown in Fig.3. Prompt and non-prompt J/ψ yields exhibit a similar pattern except in the high-$z_{J/\psi}$ region, corresponding mainly to high-$p_{\rm T}$ isolated J/ψ in jets.

3. – Multiplicity dependence of quarkonium production in pp collisions

The inclusive self-normalized J/ψ yield as a function of the self-normalized charged particle multiplicity at midrapidity has been measured by ALICE, both at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV and at forward rapidity at $\sqrt{s}$ = 5.02 and 13 TeV [9, 10]. In the case of forward quarkonia (Fig. 4, left and center plots), one can observe an approximately linear increase in the self-normalized yields as the charged particle

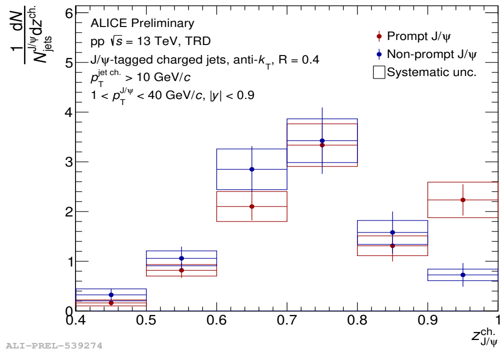

Fig. 3. – New preliminary measurement of prompt and non-prompt J/ψ production as a function of $z_{J/\psi}$ (*i.e.* the fraction of the jet momentum carried by the J/ψ) in charged jets for pp collisions at $\sqrt{s}$ = 13 TeV at midrapidity.

multiplicity grows. In contrast, midrapidity results exhibit a faster-than-linear pattern (Fig. 4, right plot). The results have been compared to several phenomenological models such as a) Percolation [11], b) 3-Pomeron Color Glass Condensate (CGC) [14], c) CGC coupled with ICEM (CGC+ICEM) [12], and d) Coherent Particles Production (CPP) [13] as well as with Monte Carlo event generators such as PYTHIA8.2 [15] and EPOS3 [16]. Good agreement is observed with CPP, Percolation, and 3-Pomeron CGC models in both rapidity intervals, within uncertainties.

ALICE provided a similar measurement for the $\psi(2S)$ in the dimuon decay channel at forward rapidity and $\sqrt{s}$ = 13 TeV [17]. The self-normalized $\psi(2S)$ yield (not shown here) exhibits a linear trend versus the midrapidity self-normalized charged particle multiplicity, as observed for forward J/ψ. PYTHIA predictions reproduce the data up to five times the average charged-particle multiplicity with and without Color Reconnection

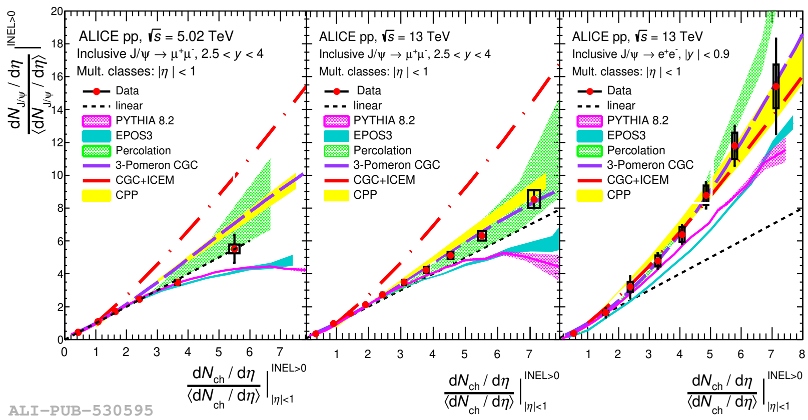

Fig. 4. – Self-normalized yield as a function of the self-normalized charged particle multiplicity measured at midrapidity for forward rapidity J/ψ in pp collisions at $\sqrt{s}$ = 5.02 TeV (left panel) and at $\sqrt{s}$ = 13 TeV (middle panel), and for midrapidity J/ψ at $\sqrt{s}$ = 13 TeV (right panel).

(CR) processes, suggesting that charmonium is not sensible to the details of the parton shower mechanism.

ALICE has provided corresponding results also in the bottomonium sector by measuring the forward Υ(nS) self-normalized yield versus the midrapidity self-normalized charged particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV [18] (not shown). The data exhibit a linear trend as observed in the charmonium sector, with a slope close to unity within uncertainties. The CPP model can reproduce the Υ(1S) and Υ(2S) data within experimental uncertainties, while the 3-Pomeron CGC overestimates the Υ(1S) results in the region above four times the average multiplicity.

4. – Summary and conclusions

This contribution has presented a selection of quarkonium and heavy-quarks production results in pp collisions, obtained by ALICE in a wide rapidity range. The J/ψ production cross section has been measured both at mid and forward rapidity, either inclusively (forward-y) or for the prompt and non-prompt component separately (mid-y), at different collision energies, from $\sqrt{s} = 5.02$ to 13 TeV. The inclusive J/ψ data are fairly described by NRQCD and ICEM theoretical calculations (coupled with FONLL to consider the beauty feed-down for the inclusive measurement). New preliminary results on J/ψ production in charged jets, as well as charm and beauty production cross sections have been recently provided by ALICE. The first one helps in understanding better the interplay between the heavy-quark fragmentation and the underlying event. The latter complements previously obtained results at midrapidity, by measuring inclusive charm and beauty cross section with dimuons at forward rapidity. The quarkonium production at both mid and forward rapidity has also been studied as a function of the midrapidity charged-particle multiplicity. For forward quarkonia, an approximate linear growth of the self-normalized yields with the charged particle multiplicity is observed, while for midrapidity charmonia a faster-than-linear trend is observed. The exact origin of this different behavior is not completely understood but CPP, 3-Pomeron CGC, and Percolation models can reproduce the data in both rapidity intervals.

REFERENCES

[1] LANSBERG J., *Physics Reports*, **89** (2020) 1.
[2] ACHARYA S. *et al.*, [ALICE], *JINST*, **3** (2008) 1.
[3] ACHARYA S. *et al.*, [ALICE], *Eur. Phys. J*, **83** (2023) 61.
[4] BUTENSCÖN M. *et al.*, *Phys. Rev. Lett.*, **106** (2011) 022003.
[5] CHEUNG M. *et al.*, *Phys. Rev. D*, **98** (2018) 114019.
[6] CACCIARI M. *et al*, *JHEP*, **137** (2012) 137.
[7] ACHARYA S. *et al.*, [ALICE], *JHEP*, **190** (2022) 190.
[8] ACHARYA S. *et al.*, [ALICE], *Phys. Lett. B*, **788** (2019) 505.
[9] ACHARYA S. *et al.*, [ALICE], *JHEP*, **15** (2022) 015,
[10] ACHARYA S. *et al.*, [ALICE], *Phys. Lett. B*, **810** (2020) 135758.
[11] FERREIRO E. *et al.*, *Phys. Rev. C*, **86** (2012) 034903.
[12] MA Y. *et al.*, *Phys. Rev. D*, **98** (2018) 074025.
[13] KOPELIOVICH B. *et al.*, *Phys. Rev. D*, **101** (2020) 044023.
[14] SIDDIKOV M.*et al.*, *Eur.Phys.J.C*, **80** (2020) 560.
[15] SJöSTRAND T. *et al.*, *Compu. Phys. Commun.*, **191** (2015) 159.
[16] WERNER, K. *et al.*, *Phys. Rev. C*, **89** (2014) 064903.
[17] ACHARYA S. *et al.*, [ALICE], *JHEP*, **6** (2023) 147.
[18] ACHARYA S. *et al.*, [ALICE], CERN-EP-2022-174 (2022)