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Quarkonium production and elliptic flow in small systems measured with ALICE

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Abstract. Quarkonium production in hadronic collisions provides a unique testing ground for understanding quantum chromodynamics (QCD) since it involves both perturbative and non-perturbative regimes of this theory. A variety of experimental observables, such as the production cross-section, polarization, particle correlations, serve as insights into the phenomenology of the quarkonium production and help constrain the theoretical models. Measurements of quarkonia as a function of multiplicity probe multiple parton interactions (MPI), i.e., several parton-parton interactions occurring in a single hadron-hadron collision. Finally, measurements of the azimuthal correlation structure of emitted particles in high multiplicity pp collisions can probe the existence of collective behaviour in small systems. The ALICE detector can reconstruct inclusive quarkonia over a broad kinematical range, spanning from mid-rapidity up to forward rapidity, and down to zero transverse momentum. In addition, at midrapidity, the non-prompt charmonium contribution can be separated from the prompt contribution. In these proceedings, we present new results on the inclusive, prompt and non-prompt J/ψ production cross sections measured by ALICE in pp collisions at different collision energies. The self-normalized ψ(2S)-to-J/ψ yield ratio measurement is investigated as a function of the charged particle multiplicity in pp collisions at $\sqrt{s}$ = 13 TeV. Finally, the first measurement of the J/ψ elliptic flow (v_2) in high multiplicity pp collisions at $\sqrt{s}$ = 13 TeV is presented. Results will be compared to theoretical models.

1 Introduction

The ALICE detector at the LHC is designed to study ultra-relativistic heavy-ion collisions (A–A). In order to understand the quarkonium production mechanisms in A–A, it is important to study its production in pp collisions. In particular, these measurements are considered a reference for nucleus-nucleus and proton-nucleus measurements, the former being used to probe the quark-gluon plasma formation and the latter to investigate cold nuclear matter effects. Results in pp collisions are also crucial for studying perturbative and non-perturbative quantum chromodynamics (QCD) aspects in vacuum [1]. Notably, pp collisions allow constraining theoretical models describing charmonium production, including the non-prompt contribution, originating from beauty hadron decays [1–3]. In addition, measurements of multiplicity-dependent quarkonium production shed light on multiple parton-parton interactions (MPI). MPI are proposed as a possible explanation for the observed collective behavior

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in high-multiplicity pp collisions [4, 5]. The ALICE detector can measure inclusive quarkonium down to zero p_{T} in two rapidity regions. At midrapidity ($|y| < 0.9$), quarkonium measurements are performed through their dielectron decay channel and separation of prompt and non-prompt contributions is achievable. At forward rapidity ($2.5 < y < 4$), inclusive quarkonium states are measured through their dimuon decay channel. The main detectors used at midrapidity for the measurements presented in these proceedings are the Inner Tracking System (ITS), providing tracking, primary and secondary vertexing determination. The ITS innermost layers compose the Silicon Pixel Detectors (SPD), used for charged particle multiplicity measurements. Finally, the Time Projection Chamber (TPC) provides tracking and particle identification. The measurements at forward rapidity are performed with the muon spectrometer, which provides reconstruction and identification of muon tracks. A description of the ALICE apparatus can be found in [6].

2 Results

The p_{T}-differential cross section measurements for the inclusive J/ψ are presented in Fig. 1 (top left panel) at forward rapidity and for various collision energies ranging from $\sqrt{s} = 5.02$ to 13 TeV [7]. An increase of the cross section is observed with increasing collision energy. Data are compared with calculations using NRQCD [8] to describe the prompt J/ψ production summed with FONLL [3] calculation for the non-prompt J/ψ contribution. The measured J/ψ cross section is in good agreement with the NRQCD + FONLL models within uncertainties, for all colliding energies. In addition, a hardening of the inclusive J/ψ p_{T}-differential spectra at $\sqrt{s} = 13$ TeV is noticed with respect to lower energies. This hardening can arise from the increase of the prompt J/ψ mean p_{T} with increasing energy, and from the increase of the non-prompt J/ψ contribution at high p_{T} (as predicted by FONLL). In Fig. 1 (bottom left panel), the cross sections ratios for different collision energies to the results at $\sqrt{s} = 13$ TeV are presented. In these ratios, partial cancellation of theoretical and experimental uncertainties occur, leading to stronger constraints on models when compared to data. An agreement within uncertainties between data and the models for the 8-to-13 TeV and 5.0-to-13 TeV ratios is observed. The 7-to-13 TeV ratio is slightly overestimated by NRQCD+FONLL model, the latter expecting values closer to the 8-to-13 TeV ratio.

The self-normalized ψ(2S)-to-J/ψ yield ratio at forward rapidity is presented as a function of the self-normalized charged particle multiplicity at midrapidity in Fig. 1 (right panel) [9]. The self-normalized ratio is compatible with unity, indicating that the multiplicity dependence of the charmonium production at forward rapidity is similar for the J/ψ and ψ(2S) states. The data is compared with PYTHIA8 [10], which considers MPI for heavy-flavour productions, with and without colour reconnections. A comparison is also made with the comovers model [11]. The latter considers a quarkonia dissociation effect, particularly affecting the less bound ψ(2S) excited state, due to its interactions with the final state comoving particles. The PYTHIA8 model describes data fairly considering the uncertainties. However, there is tension at low multiplicity, where the ratio is underestimated. As for comovers calculations, an agreement between data and the model can be observed within the large experimental uncertainties. The model suggests a decreasing ratio with the increasing multiplicity, which is not strongly supported by the current data.

The p_{T}-differential cross section for prompt and non-prompt J/ψ, measured at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV are presented in Fig. 2 [12]. The prompt J/ψ p_{T}-differential cross section (Fig. 2 left) is compared with ICEM [2] and several NRQCD based models (see corresonding Refs. in [12]). Compatibility within uncertainties is noticed between data and models, except for the NRQCD Lipatov calculations [13], which slightly overestimate data at

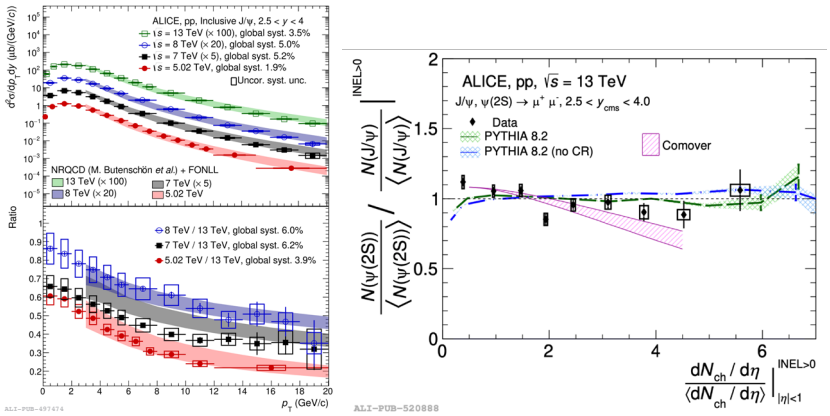

Figure 1. (left) The inclusive J/ψ p_{T}-differential cross section (top), and the ratio of the 5.02, 7, and 8 TeV cross sections to the 13 TeV one (bottom), at forward rapidity, in pp collisions [7]. (right) The self-normalised ψ(2S)-to-J/ψ yield ratio measured at forward rapidity as a function of the charged particle multiplicity measured at midrapidity, in pp collisions at $\sqrt{s}$ = 13 TeV [9].

low p_{T}. An agreement is observed between the non-prompt J/ψ p_{T}-differential cross section at $\sqrt{s}$ = 13 TeV and the FONLL model (Fig. 2 right).

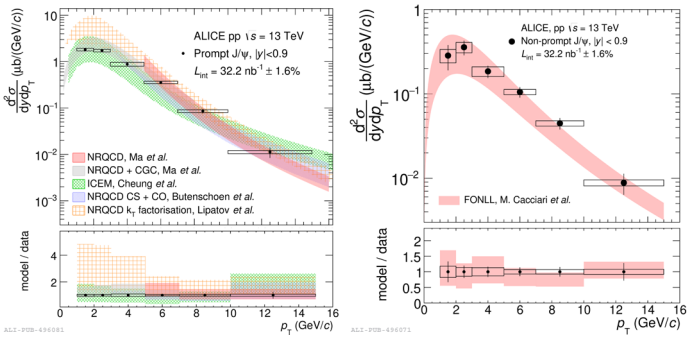

Figure 2. The prompt (left) and non-prompt (right) J/ψ cross section as a function of p_{T}, in pp collisions at $\sqrt{s}$ = 13 TeV and midrapidity [12].

Finally, to investigate eventual collective effects on quarkonium production in pp collisions, the J/ψ v_2 coefficient is extracted in high multiplicity pp collisions at $\sqrt{s}$ = 13 TeV, using the two-particle correlation technique. The resulting v_2 is presented in Fig. 3 down to p_{T} = 0 GeV/c, and is compared to similar results in p–Pb [14], and Pb–Pb [15] collisions at forward rapidity. In p–Pb and Pb–Pb, the inclusive J/ψ exhibits a positive v_2, which is interpreted as a sign of collectivity. As a first comparison, the following ordering of the J/ψ v_2 across systems is observed: $v_{2,J/\psi}^{pp} < v_{2,J/\psi}^{pPb} < v_{2,J/\psi}^{PbPb}$. No significant deviation from zero of the J/ψ v_2 is noted in pp collisions. The same observation can be made for the p_{T}-integrated J/ψ v_2, as its deviation from zero is within about 1 σ. Thus, there is no indication of collective behavior for the J/ψ within uncertainties, in pp collisions.

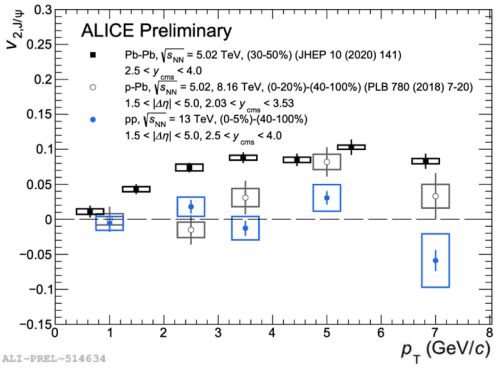

Figure 3. The inclusive J/ψ v_2 measured at forward rapidity in pp, p–Pb [14] and Pb–Pb [15] collisions.

3 Summary

The inclusive J/ψ p_{T}-differential cross section is presented in pp collisions at $\sqrt{s}$ = 5.02, 7, 8, and 13 TeV and at forward rapidity. NRQCD + FONLL describe well the data within uncertainties. Measurement of multiplicity-dependent self-normalized ψ(2S)-to-J/ψ yield ratio at $\sqrt{s}$ = 13 TeV is also shown. This is found to be compatible with unity within uncertainties, pointing that the multiplicity dependence of the charmonium production is similar for J/ψ and ψ(2S) states. Data is well described within uncertainties by PYTHIA8 and comovers, with some tensions observed notably at very low or high multiplicity, depending on the model. The p_{T}-differential cross section measurements at midrapidity are also presented separately for prompt and non-prompt J/ψ in pp collisions at $\sqrt{s}$ = 13 TeV. A good agreement within uncertainties is observed between NRQCD and prompt J/ψ data, as well as FONLL and non-prompt J/ψ data. Finally, the inclusive J/ψ elliptic flow at forward rapidity is presented in high multiplicity pp collisions. No significant collective behavior can be observed.

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