PROCEEDINGS OF SCIENCE

Charmonium production in pp and p–Pb collisions with ALICE

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Charmonium production studies in hadronic collisions are a powerful tool for improving our understanding of quantum chronodynamics (QCD), the theory of the strong interaction. The production of the charm-quark pair can be described within perturbative QCD, whereas the evolution of this pair into a colorless bound state involves soft scale processes. In addition, multiplicity dependent studies of charmonia in both proton-proton (pp) and proton-lead (p–Pb) collisions can shed light on the role of multiple parton interactions (MPI) for heavy-quark production. Furthermore, charmonia in small systems are fundamental to understand the properties of the quark-gluon plasma (QGP) created in heavy-ion collisions. Potential initial-state effects can be constrained using results in p–Pb, while reference measurements in pp collisions offer a basis for the vacuum production at the same center-of-mass energy.

The ALICE detector has unique capabilities at the LHC for measuring quarkonia down to zero transverse momentum. Measurements are carried out at both central and forward rapidity, in the dielectron and dimuon decay channel, respectively.

In this contribution an overview of the latest results of charmonium production in pp and p–Pb collisions at several centre-of-mass energies will be presented.

**** 10th International Workshop on Charm Physics (CHARM2020), ****
**** 31 May - 4 June, 2021 ****
**** Mexico City, Mexico - Online ****

*Speaker

PoS(CHARM2020)028

1. Physics motivations

Charmonia are flavorless mesons consisting of a charm-anticharm quark pair. Studies of charmonium production in hadronic collisions provide a unique window into the QCD realm, the theory of the strong interaction. Studying charmonia through proton-proton collisions enables insight into the production mechanisms at the partonic level, and gives a benchmark for perturbative QCD and non-perturbative QCD-based models. It also provides a reference for p-Pb and Pb-Pb studies at the same centre-of-mass energy.

Charmonium studies in p-Pb collisions are important in order to understand effects due to the presence of cold nuclear matter, such as shadowing modifications due to the nucelar environment to the parton distribution functions (PDFs), colour glass condensate, parton energy loss and final state interaction (absorption, comovers). In addition, the investigation of possible collective effects on charm quarks in p-Pb collisions has become a topic of special interest after the discovery of the double ridge found in charged-particle correlations at mid- and forward rapidity [1–4].

Furthermore, the study of charmonium production as a function of the charged particle multiplicity in small systems allows to investigate how the multiple parton interactions (MPI) contributes to the production of the charm quarks, as well as the interplay between hard and soft particle production mechanisms in the same event.

2. Charmonium measurements in ALICE

The ALICE detector provides charmonium detection down to $p_{\mathrm{T}} = 0$ through either dimuon or dielectron decay channels at forward ($2.5 < y < 4$) or midrapidity ($|y| < 0.9$), respectively.

At midrapidity the charmonium states are reconstructed using the Inner Tracking System (ITS), which consists of six cylindrical layers of silicon detectors employing different technologies. The ITS provides high resolution for secondary vertex reconstruction, enabling the measurement of the fraction of "non-prompt" J/ψ, originating from beauty-hadron decays. The Time Projection Chamber provides reconstruction of the tracks, in combination of the ITS, and particle identification via specific energy loss measurements.

The forward muon spectrometer includes a dipole magnet with an integrated field of 3 T·m, five tracking stations comprising two planes of cathode pad chambers each, and two trigger stations consisting of two planes of resistive plate chambers each. The latter allows to trigger on events with at least a pair of opposite-sign track segments in the muon trigger system, each with a p_{T} above a specific threshold. A system of absorbers is used for filtering out hadrons.

3. Selected highlights in pp collisions

The midrapidity p_{T}-differential cross sections of prompt J/ψ at $\sqrt{s}$ = 13 and 5 TeV [5], obtained from the combination of inclusive cross section and non-prompt J/ψ fraction measurements, are shown in Fig. 1 in the left and right hand panels, respectively. The prompt J/ψ cross sections at $\sqrt{s}$ = 5 TeV are found to be consistent with midrapidity measurements performed at the same centre-of-mass energies by ATLAS [6] and CMS [7] collaborations. The measurements at both centre-of-mass energies are compared with theoretical calculations performed using non-relativistic quantum chromodynamics (NRQCD) based models and the improved colour evaporation model (CEM). Both sets of calculations show good agreement with the data within the uncertainties, although the large uncertainties of the model calculations prevent any strong conclusion.

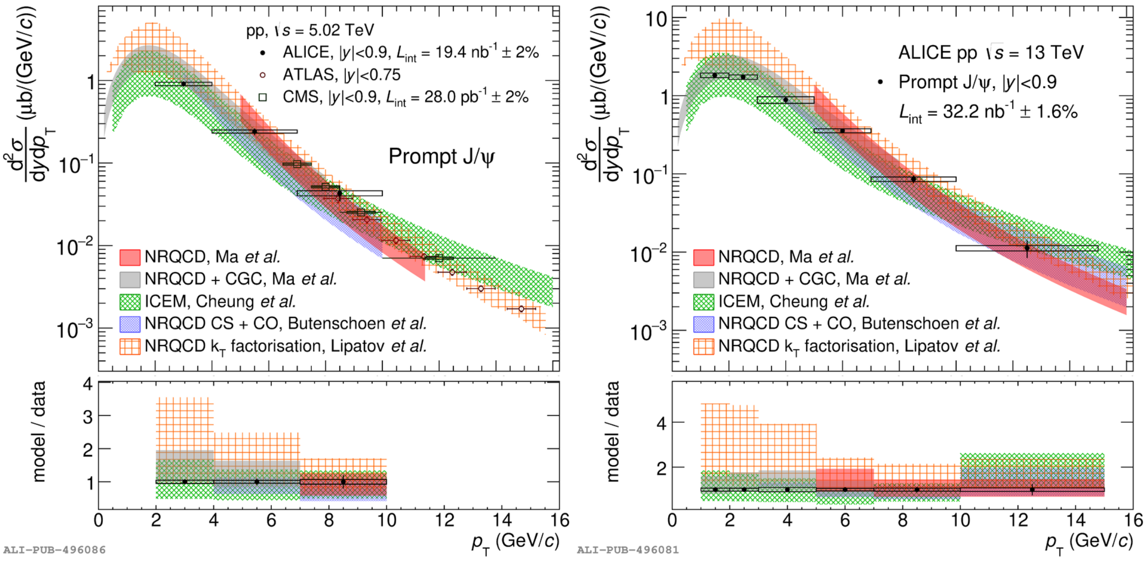

Figure 1: ALICE cross section measurements of prompt J/ψ for 5.02 TeV (left) and 13 TeV (right), compared to theoretical model calculations [5]. Results at $\sqrt{s}$ = 5.02 TeV are compared with CMS [7] and ATLAS [6] measurements at high p_{T}. Bottom panels show ratios of the models to ALICE results.

The forward rapidity J/ψ p_{T}-differential cross section measurements at different $\sqrt{s}$ are shown in the left-hand panel of Fig. 2 [8]. The comparison indicates a hardening of the spectra with increasing centre-of-mass energy. The ψ(2S) p_{T}-differential cross section at $\sqrt{s}$ = 13 TeV is compared to NRQCD calculations with FONLL model calculations added on top in the right-hand panel of Fig. 2 [8]. There is a good agreement observed between the model and the data for the measured cross sections.

4. Selected highlights in p-Pb collisions

In Fig. 3, the nuclear modification factor R_{pPb} measured in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV is shown as a function of y_{cms}, the rapidity in the centre-of-mass system, for both J/ψ and ψ(2S) [12]. The R_{pPb} is defined as the production cross section in proton-nucleus collisions divided by that in pp collisions at the same energy, scaled by the atomic mass number A. It is used to quantify cold nuclear matter effects and one would expect R_{pPb} to be equal to one if there were no nuclear effects. Both J/ψ and ψ(2S) show similar suppression at forward rapidity. However, at backward rapidity the ψ(2S) is much more suppressed than J/ψ. In order to reproduce the ψ(2S) in models, one needs to include final state interactions with the surrounding medium.

In the left (right) panel of Fig. 4 the cross section (R_{pPb}) of the prompt J/ψ measured in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV is shown together with forward and backward rapidity results from LHCb [13]. The cross section is compared to models including nuclear shadowing based on different sets of nuclear PDFs. The R_{pPb} is compared to model predictions implementing different cold nuclear matter (CNM) effects. Both measurements sit in the upper band of the models.

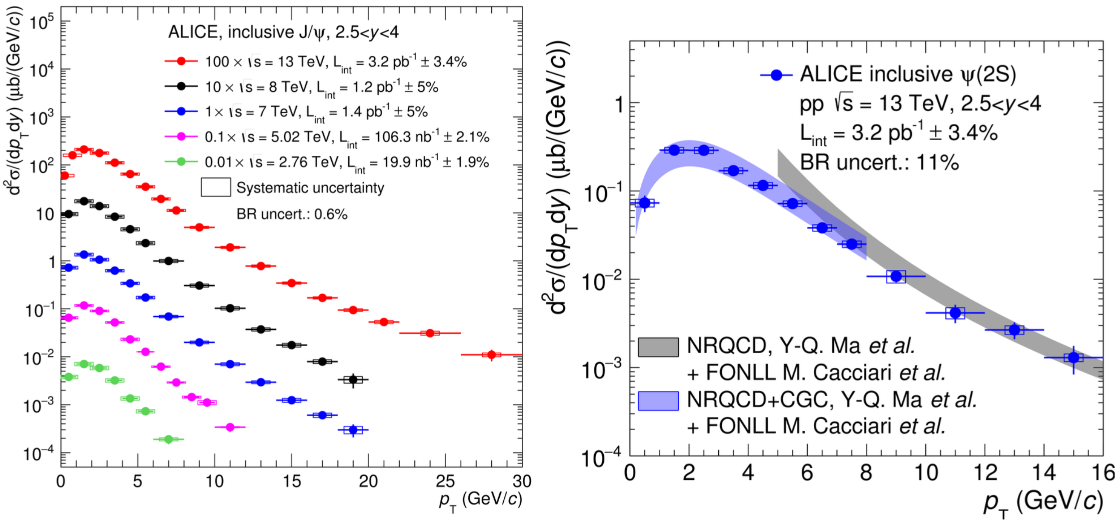

Figure 2: Left: inclusive J/ψ cross sections for pp collisions at several centre-of-mass energies measured at forward rapidity as a function of the transverse momentum [8]. Right: inclusive ψ(2S) cross section at $\sqrt{s}$ = 13 TeV compared to models [9] [10] [11]

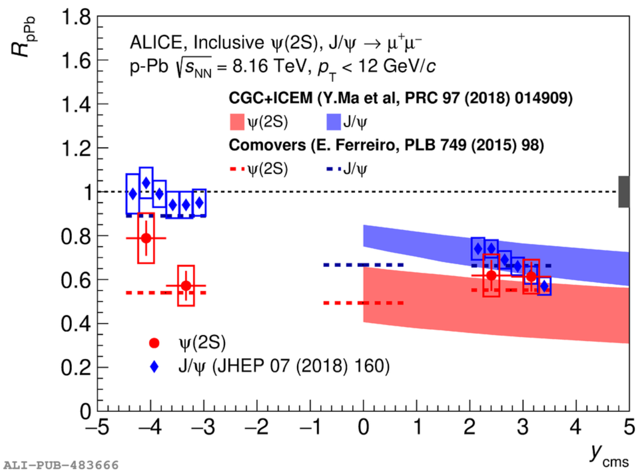

Figure 3: R_{pPb} as a function of y_{cms} for ψ(2S) and J/ψ p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV [12]. Theoretical models are shown for comparison (references on the plot).

5. Conclusions and future perspectives

Selected charmonium measurements in pp and p-Pb collisions performed by the ALICE Collaboration are presented. In pp collisions at $\sqrt{s}$ = 5 and 13 TeV theoretical models describe within uncertainties prompt J/ψ cross sections measured at midrapidity. No conclusion can be drawn due to the large model uncertainties. At forward rapidity $\psi(2S)$ cross section is compatible with NRQCD based models. In p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV theoretical models describe well the charmonium results at forward rapidity, although stronger suppression of the ψ(2S) with respect to J/ψ at backward rapidity necessitates final state interactions included in the calculations. Prompt J/ψ

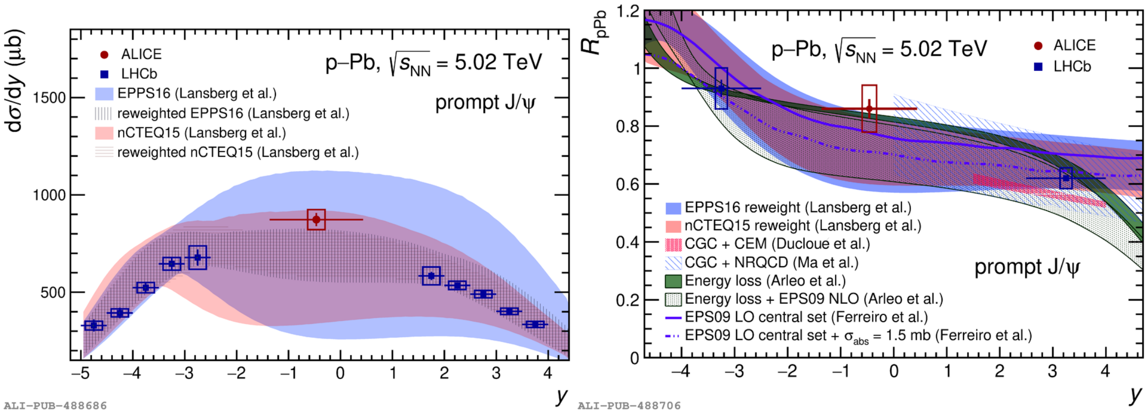

Figure 4: The midrapidity production cross section and R_{pPb} of the prompt J/ψ in the left and right hand panels, respectively. Results are compared with LHCb measurements [13] as well as with theoretical models (see [14] and references therein).

cross section and $R_{\rm pPb}$ measured at midrapidity in p-Pb at $\sqrt{s_{\rm NN}}$ = 5.02 TeV are found compatible with theoretical calculations, sitting in the upper band of the models.

Run 3 and Run 4 will bring great opportunities for charmonium measurements in the near future as the ALICE detector is going through a major upgrade [15]. With expected integrated luminosities of 200 pb^{-1} in pp collisions at $\sqrt{s}$ = 14 TeV and 500 nb^{-1} in p-Pb collisions $\sqrt{s_{\rm NN}}$ = 8.8 TeV, as well as with the improved spatial resolution provided by the upgraded ITS, existing mid-rapidity charmonium measurements will be improved significantly and a set of new observables will become accessible [16, 17]. In addition, reconstruction of secondary vertices at forward rapidity will be enabled through the new Muon Forward Tracker.

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