RESULTS ON RESONANCE PRODUCTION IN HEAVY-ION COLLISIONS FROM THE ATLAS EXPERIMENT AT THE LHC*

Jakub Kremer

on behalf of the ATLAS Collaboration

AGH University of Science and Technology
Faculty of Physics and Applied Computer Science
al. Mickiewicza 30, 30-059 Kraków, Poland

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Recent ATLAS measurements of quarkonia and open charm production are presented for proton–lead and lead–lead collisions. The studies of charmonia production in ultrarelativistic nucleus–nucleus collisions offer a handle on the properties of the hot and dense quark–gluon plasma created in these collisions. In particular, a strong suppression relative to proton–proton collisions is expected. On the other hand, measurements of quarkonia and charmed meson production in proton–nucleus collisions allow to study cold nuclear matter effects such as initial-state energy loss or nuclear modifications of parton distribution functions.

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1. Introduction

Resonances containing heavy (c, b) quarks are excellent probes to study the nuclear matter involved in heavy-ion collisions at the LHC energies. In nucleus–nucleus collisions, heavy quarks are produced in hard processes and thus probe the full evolution of the hot and dense quark–gluon plasma (QGP) formed later in these collisions [1]. However, the effects of their interaction with the QGP are entangled with initial-state effects such as incoming parton energy loss or nuclear modifications of parton distribution functions (nPDFs). These can be studied separately in proton–nucleus collisions.

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The modification of the production of heavy-flavour probes in proton–lead (p+Pb) collisions relative to proton–proton (pp) collisions can be studied by using the nuclear modification factor defined as

$$R_{p\mathrm{Pb}} = \frac{1}{A_{\mathrm{Pb}}} \frac{\sigma_{p+\mathrm{Pb}}}{\sigma_{pp}}\,, \tag{1}$$

where $\sigma_{p+\mathrm{Pb}}$ and σ_{pp} are cross sections for the production of a given heavy-flavour probe measured in p+Pb and pp collisions, respectively, and $A_{\mathrm{Pb}} = 208$ is the mass number of lead nuclei used for heavy-ion studies at the LHC. For lead–lead (Pb+Pb) collisions, the nuclear modification factor is defined in the following way:

$$R_{AA} = \frac{N_{AA}/N_{\mathrm{evt}}}{\langle T_{AA}\rangle\, \sigma_{pp}}\,, \tag{2}$$

where N_{AA} is the yield of a given heavy-flavour probe, N_{evt} is the number of sampled minimum-bias Pb+Pb collisions and $\langle T_{AA}\rangle$ is the average nuclear overlap function [2].

Information complementary to the studies of production modifications of heavy-flavour resonances can be obtained from flow measurements. The elliptic flow coefficient v_2 is defined using the Fourier expansion of the particle yields N in the azimuthal angle ϕ

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi - \Psi_n\right)\right], \tag{3}$$

where Ψ_n is the n^{th} harmonic of the event-plane angle.

This report presents the following measurements of heavy-flavour production in heavy-ion collisions made using the ATLAS detector [3]: charmonia production in pp, p+Pb and Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [4, 5], J/ψ flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [6], as well as bottomonia production in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [4], and D-meson production and flow in p+Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [7].

2. Quarkonia measurements

ATLAS performs quarkonia measurements in heavy-ion collisions in the dimuon decay channels. Therefore, events collected with triggers requiring at least two muons are used. Quarkonia candidates are constructed from oppositely charged muon pairs originating from a common decay vertex and having an invariant mass, $m_{\mu\mu}$, in a certain range around the quarkonium mass. Charmonia yields are extracted from a simultaneous fit to distributions of $m_{\mu\mu}$ and pseudo-proper lifetime $\tau_{\mu\mu}$ [4]. This method allows to separate prompt charmonia production and non-prompt production, where the latter is dominated by B-hadron decays outside of the QGP volume. Bottomonia yields are extracted from fits to the $m_{\mu\mu}$ distribution.

Figure 1 presents R_{AA} measured as a function of transverse momentum, $p_{\rm T}$, for prompt and non-prompt J/ψ mesons in different centrality classes. In addition, it shows the comparison of the measured prompt J/ψ R_{AA} with predictions of several theoretical models. The R_{AA} for prompt J/ψ production is increasing slowly with $p_{\rm T}$, while the magnitude of suppression of non-prompt production is constant. For both types of production, a strong suppression is observed in Pb+Pb collisions, which increases rapidly with centrality. The modification of prompt J/ψ production is consistent both with energy loss models and the colour screening picture.

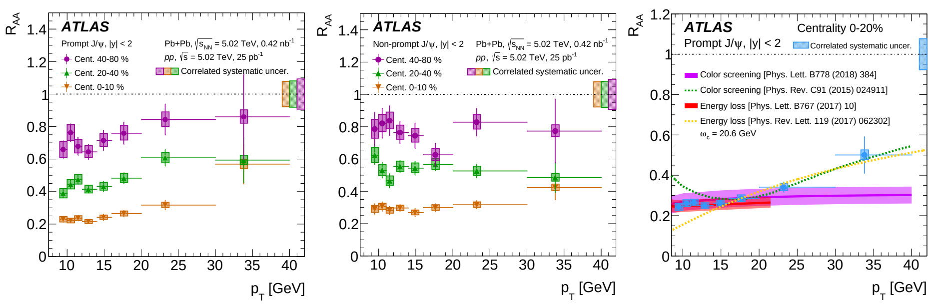

Fig. 1. The nuclear modification factor as a function of $p_{\rm T}$ for the prompt J/ψ (left) and non-prompt J/ψ (middle) for $|y| < 2$, in 0–10%, 20–40%, and 40–80% centrality bins. The right panel shows a comparison of the R_{AA} for prompt J/ψ production with different theoretical models. The statistical uncertainty of each point is indicated by an error bar. The error box plotted with each point represents the uncorrelated systematic uncertainty, while the shaded error box at $R_{AA} = 1$ represents correlated scale uncertainties [5].

Figure 2 shows the elliptic flow coefficient v_2 for prompt and non-prompt J/ψ mesons measured as a function of centrality. The measurements favour non-zero v_2 values for both types of production, with no significant centrality dependence.

The nuclear modification factors $R_{p\rm Pb}$ for $\Upsilon(1S)$ production are shown in figure 3 as a function of $p_{\rm T}$ and centre-of-mass rapidity y^*. A suppression of $\Upsilon(1S)$ production is observed at low $p_{\rm T}$, which is constant over the considered rapidity range. This hints at nuclear modifications of parton distributions at low x. No significant modification of charmonia production is observed [4].

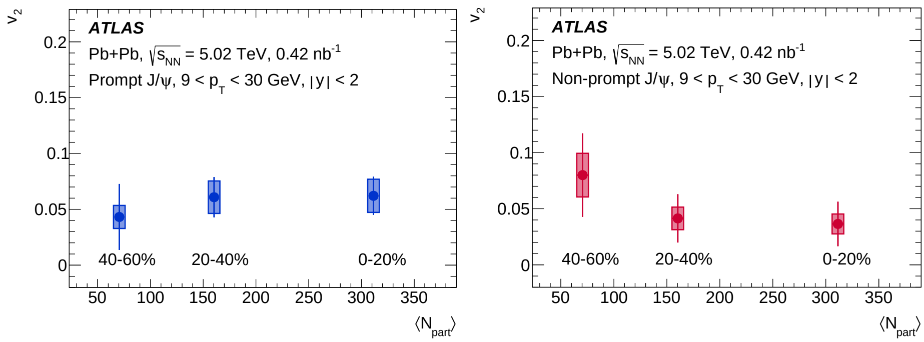

Fig. 2. Prompt (left) and non-prompt (right) J/ψ v_2 as a function of average number of nucleons participating in the collision for transverse momentum in the range of $9 < p_{\mathrm{T}} < 30$ GeV and rapidity $|y| < 2$. The statistical and systematic uncertainties are shown using vertical error bars and boxes, respectively. The centrality interval associated to a given value of $\langle N_{\mathrm{part}}\rangle$ is written below each data point [6].

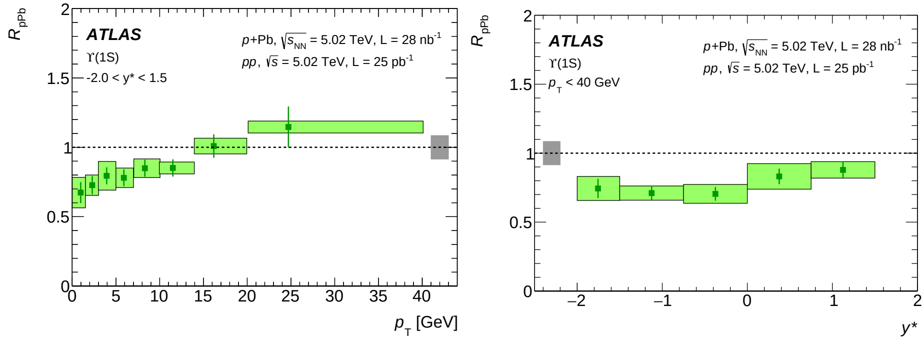

Fig. 3. (Colour on-line) The nuclear modification factor, $R_{p\mathrm{Pb}}$, as a function of transverse momentum p_{T} (left) and centre-of-mass rapidity y^* (right) for $\Upsilon(1S)$. The horizontal position of each data point indicates the mean of the weighted p_{T} or y^* distribution. The vertical error bars correspond to the statistical uncertainties. The vertical sizes of grey (green) boxes around the data points represent the uncorrelated systematic uncertainties, and the horizontal sizes of grey (green) boxes represent the bin sizes. The vertical size of the rightmost (left) and leftmost (right) dark grey boxes around $R_{p\mathrm{Pb}} = 1$ represents the correlated systematic uncertainty [4].

3. *D*-meson measurements

The D-meson measurements in p+Pb collision utilise the following decay channels: $D^0 \to K\pi$ and $D^* \to D^0\pi$. Candidates for D^0 mesons are built from opposite-sign pairs of charged-particle tracks, while D^*-meson candidates require an additional soft pion track. Yields of D^0 mesons are extracted from fits to the invariant mass distribution of the track pair, $m(K\pi)$, accounting for the kaon and pion masses. For D^* mesons, the yield extraction proceeds via fits to the distribution of the difference between the three-track invariant mass, $m(K\pi\pi)$, and $m(K\pi)$. The non-prompt contributions to D-meson yields are subtracted based on theoretical calculations of $b \to D$ cross sections.

Modifications of D-meson production are studied using the forward-to-backward ratio of differential production cross sections $\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*$

$$R_{\mathrm{FB}} = \frac{\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*\,(0 < y^* < 0.5)}{\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*\,(-0.5 < y^* < 0)}\,. \tag{4}$$

Figure 4 shows R_{FB} for prompt D mesons measured as a function of p_{T}. Within the considered rapidity range, $|y^*| < 0.5$, no significant deviation of R_{FB} from unity is observed.

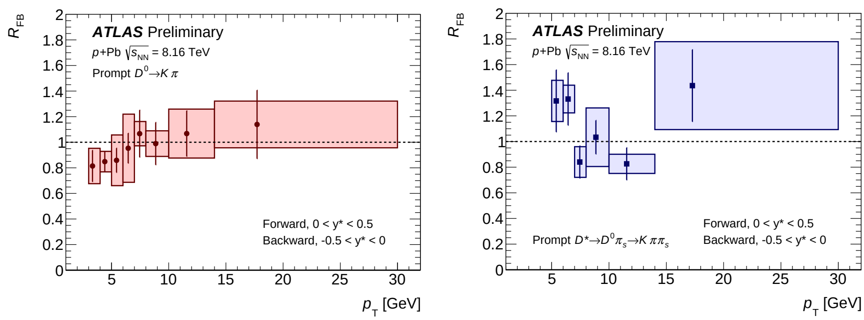

Fig. 4. Forward-to-backward yield ratio, R_{FB}, of prompt D^0 (left) and prompt D^* (right) as a function of p_{T} in p+Pb collisions at 8.16 TeV. The vertical error bars cover only statistical uncertainties. The horizontal sizes of the boxes around data points represent the width of the bin, while the vertical sizes of the boxes indicate the systematic uncertainties [7].

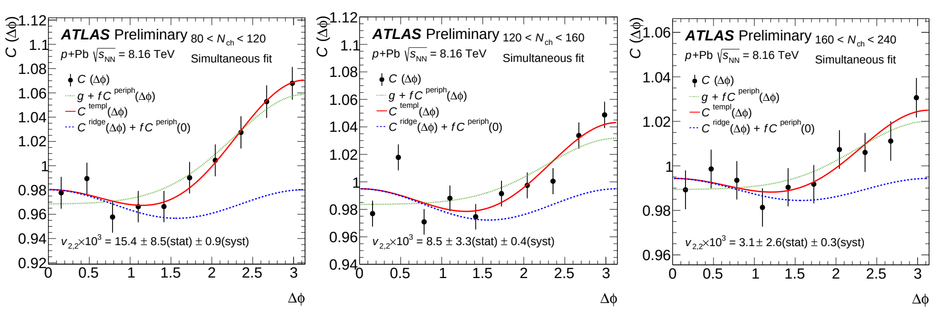

Fig. 5. Template fits to the D^*–h correlation function for different track multiplicity intervals. The low-multiplicity fit is performed to the low-multiplicity correlation function, while the other represent the fit results for multiplicity events from simultaneous fits to the low-multiplicity and higher-multiplicity correlation functions. The resulting $v_{2,2}$ value and its uncertainty are presented [7].

D^*-hadron correlations are studied using two-particle correlation functions following the method described in Ref. [8]. The correlation functions measured in several classes of charged-particle track multiplicity are shown in figure 5. In addition, simultaneous template fits used to extract the second order harmonic coefficients, $v_{2,2}$, of the two-particle correlation function are presented. The measured values of the coefficients are consistent with a non-zero elliptic flow at the level of 1–2σ for all considered multiplicity classes.

4. Summary

A summary of recent ATLAS measurements of the production and flow of heavy-flavour resonances in heavy-ion collisions is presented.

For quarkonia, it is observed in Pb+Pb collisions that charmonia production is strongly suppressed, and an evidence for elliptic flow of the J/ψ meson is found. These are clear indications of charmonia interactions with the QGP. In p+Pb collisions, no modification of charmonium production is observed, but the suppression of low-p_{T} $\Upsilon(1S)$ production suggests a nuclear modification of parton distribution functions.

For D mesons produced in p+Pb collisions, no evidence of initial-state effects is observed in the forward–backward ratios of yields. On the other hand, a hint of a non-zero elliptic flow of D^* mesons can be seen.

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